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Enantioselective Protonation of Samarium Enolates by a C_2-Symmetric Chiral Diol

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Abstract: High enantioselectivity (up to 97%ee) have been achieved in the protonation of samarium enolates which were generated by SmI_2-mediated cross-coupling reaction between unsymmtrical dialkylketene and allyl iodide, using a C_2-symmetric chiral diol as a proton source. The stereochemistry of enolate formation and of the enantioselective protonation is discussed.

Enantioselective protonation of metal enolates by chiral proton sources is a promising method for the preparation of non-racemic carbonyl compounds or carboxylic acid derivatives bearing a stereogenic carbon atom at the α-position.[1] The reaction have been investigated by many researchers since the pioneering work of Duhamel[1c] and recently some exhibiting extremely high enantioselectivity have been reported. For example, Kosugi[2a], Yamamoto[2b] and Vedejs[3] have independently reported the enantioselective protonation of lithium enolates in 97% ee. Fehr and coworkers have found the enantioselective protonation of a lithium (Z)-thiol ester enolate with almost complete enantioselectivity (99% ee) using N-isopropylephedrine as a homochiral proton source and also succeeded in extending it to a catalytic version.[4]

We have investigated an enantioselective protonation of samarium enolates which are formed by SmI_2-mediated cross-coupling reaction between dialkylketene and alkyl halide, using the C_2-symmetric homochiral diol (α,α'-di[(S)-2-hydroxy-2-phenylethyl]-o-xylenedioxide:DHPEX) as the proton source. The strategy of this study is based upon the enantioselective protonation of lithium-magnesium enolates by chiral β-aminoalcohols reported by Fehr[5] and that of samarium 1,2-diphenylethen-1,2-diolate by quinidine found by us.[6] Fehr and Galindo reported the asymmetric synthesis of (R)- and (S)-α-Damascone by Grignard reaction on the precusor ketene followed by enantioselective protonation (84% ee). In this reaction 1 equiv. lithium alkoxide of a chiral β-aminoalcohol must be added prior to the protonation for obtaining the high enantioselectivity. The formation of a mixed lithium-magnesium 1:1 complex between the ketone enolate and the alkoxide brought about a double stereodifferentiation in the protonation transition state by the chiral alcohol. This prompted us to examine the enantioselective protonation of samarium enolates in extention of SmI_2-mediated enantioselective protonation of benzil in which the samarium 1,2-diphenyethen-1,2-diolate was protonated by quinidine to afford benzoin in 91% ee. Thus we thought that high enantioselectivity should be accomplished also in the case of samarium enolate without coexistence of other metal ion such as lithium if a chiral proton source suitable for the samarium enolate could be found.

In the previous communication,[7] we reported the preliminary results on the enantioselective protonation of the enolate using DHPEX as the chiral proton source and alkylarylketenes as substrates. We describe here the results of our efforts to effect higher enantioselectivity using more general dialkylketene and of a consideration on the stereochemistry of the samarium enolate formation and the enantiose-

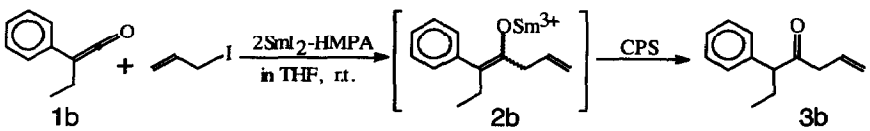
lective protonation.

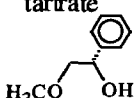
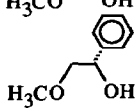
Results and Discussion

SmI_2-promoted allylation of ketene is conducted by addition of a 0.1M SmI_2 solution in THF to a solution of the ketene, allyl iodide and HMPA in THF to give the samarium enolate within a few minutes.[8] Protonation of the enolate by a chiral proton source gives the corresponding chiral ketone in good yield.

In order to find a suitable proton source and optimal reaction conditions, allylation of ethylphenylketene (**1b**) followed by the protonation using several chiral alcohols was carried out (Table 1).

Table 1. Enantioselective Protonation of the Samarium Enolate Generated by SmI_2-mediated Allylation of Ethylphenylketene.

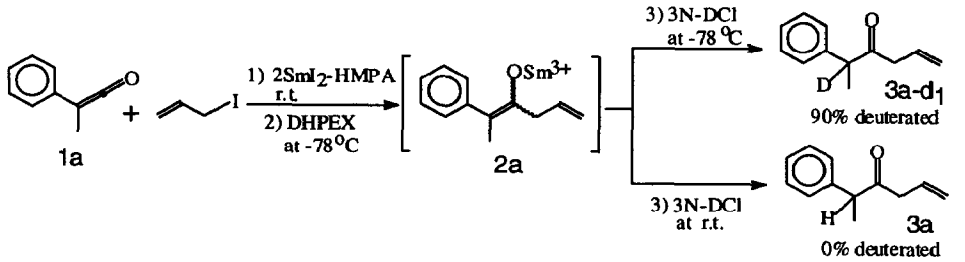


Entry	Chiral Proton Source (CPS)	Reaction Temp.	Yield / %	%ee	Config.
1	Quinidine	r.t[a)]	30[b)]	33	*S*
2	Diethyl L(+)-tartrate	r.t	70	0	—
3		r.t	80	61	*R*
4		-45 °C	52	75	*R*
5	DHPEX	r.t	60	71	*R*
6	DHPEX	-78 °C(4.5h) → r.t (20min)	62	84	*R*

a) Room temperature. b) Product whose olefinic double bond was isomerized to α,β-position was obtained.

As seen from Table 1, DHPEX gave the best result at -78 °C for 4.5 h and then at room temperature for 20 min. However, the protonation of the enolate occurs during the time the reaction temperature was raised from -78 °C to room temperature. This was demonstrated by deuteration of the enolate with 3N deuterochloric acid. After treating the enolate with DHPEX for 24 h at -78 °C, quenching the reac-

tion with 3N deuterochloric acid at -78 °C yielded the corresponding ketone chiral carbon atom of which was 90% monodeuterated but quenching after the reaction at room temperature for 20 min resulted in non-deuterated ketone, using methylphenylketene (**1a**) as substrate (Scheme 1).

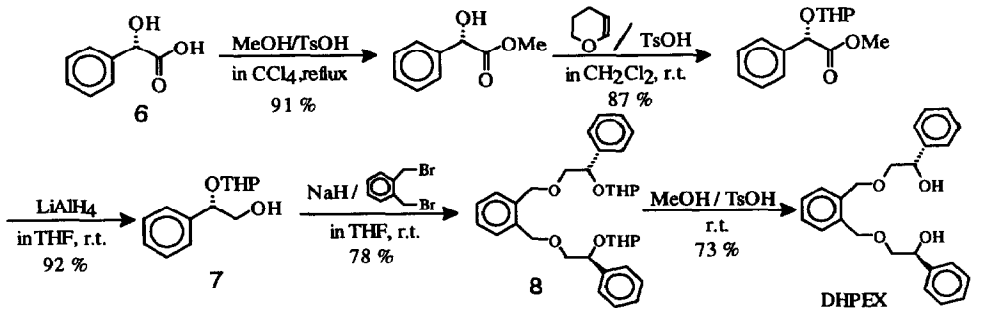


Scheme 1

Therefore, the protonation was hereafter carried out at -78 °C for 30 min and then for 40 min by permitting the solution to stand at room temperature until the solution reached room temperature using DHPEX as the chiral proton source.

The optimal molar ratio of DHPEX and HMPA to samarium were about 0.7 and 0.6 respectively: the enantioselectivity was lowered when the ratios became smaller or larger. For example, the enantioselectivity was 70% ee at DHPEX/Sm=1.0 in the case of methylphenylketene. Using HMPA at the ratio stated is requisite condition to maintain the reaction solution homogeneous at -78 °C. Without HMPA, a large amount of precipitate separated and remained insoluble even on the addition of DHPEX and resulted in a low enantioselectivity (<62% ee). Prolonged reaction times also resulted in the formation of precipitates in the case of the ketenes which have no aryl group attached directly to the β-carbon atom and lowered the enantioselectivity. Thus, when the color of the reaction solution turned orange yellow from dark blue, the solution was immediately cooled to -78 °C before the formation of precipitates and to the solution DHPEX solution in THF was added to achieve the highest enantioselectivity.

DHPEX was prepared from (S)-mandelic acid (**6**) by the following route (Scheme 2).

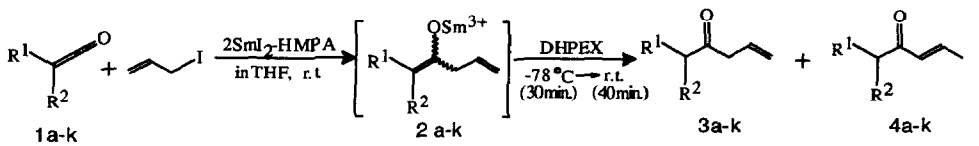


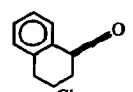
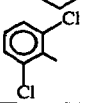
Scheme 2

(2S)-2-phenyl-2(2'-tetrahydropyranyloxy)ethanol (7) was prepared according to Stephenson's method.[9] Enantiomeric purity of DHPEX was determined to be 100% ee by HPLC analysis using DAISEL Chiralcel OJ column. The analysis was performed by using the enantiomer and the diastereomer of DHPEX as internal standards which were prepared from (R)-mandelic acid and both enantiomers of the acid, respectively. DHPEX was recovered from the reaction mixture of the enantioselective protonation in more than 96% recovery and was confirmed to be 100% ee. When the recovered DHPEX was reused essentially the same enantioselectivity was observed.

Next, we examined the enantioselective protonation using several unsymmetrical dialkylketenes. The results were summarized in Table 2.

Table 2. Enantioselective Protonation of Samarium Enolate Generated by SmI_2-mediated Allylation of Ketenes with DHPEX.



Entry	R^1	R^2		3 + 4			3 : 4 [a]
				Yield (%)	%ee	(Config.)	
1	Ph	Me	(1a)	51	91	(*R*)	>98 :2
2	Ph	Et	(1b)	62	84	(*R*)	>98 :2
3		Me	(1c)	65	97	(*R*)	91 :9
4		Me	(1d)	58	94	(*R*)	90 :10
5	t-Bu	Me	(1e)	21[b]	93	(*R*)	>98 :2
6		Me	(1f)	36	91	(*R*)	>98 :2
7		i-Pr	(1g)	68	85	(*S*)	>98 :2
8	$PhCH_2$	Et	(1h)	59	29	(*S*)	68 :32
9	$PhCH_2$	i-Pr	(1i)	64	68	(*S*)	84 :16
10			(1j)	75	48	(*R*)	53 :47
11		Me	(1k)	79	62	(*R*)	>98 :2

a) The ratio was determined by ^1HNMR analysis or by isolation (Entry 8). b) The low yield may be due to volatile nature of the product.

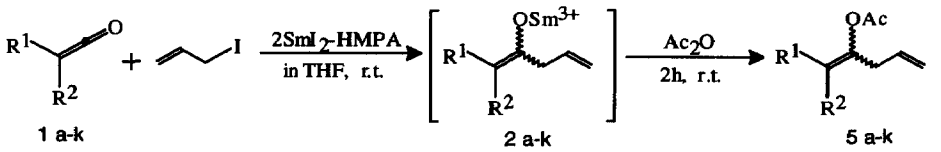
Enantiomeric excesses of the products were determined by ^{1}H NMR analysis using Eu(hfc)$_3$ as a chiral shift reagent (Entries 1-9 and 11) and/or by HPLC analysis using a chiral column (DAISEL Chiralcel OD in Entries 3, 4, and 10; Chiralcel OB' in Entries 8 and 11). The enantiomeric excess of the allylated ketone (β,γ-isomer, **3**) was essentially the same as that of its isomerized α,β-isomer (**4**) and thus the HPLC analysis was performed on the sample obtained by hydrogenation of the olefinic double bond of the product containing both isomers. The configuration of the products was determined by comparing the sign of the specific rotation, the separation mode of methyl signal of methyl, ethyl or isopropyl group attached to the stereogenic carbon atom of the ketone in ^{1}H NMR spectrum in the presence of Eu(hfc)$_3$ and the sign of the Cotton effect in the CD spectrum of the hydrogenated sample at 240-340 nm, with those of (-)-**3a**, (-)-**3b** and their hydrogeneted samples which are known to have (R)-configuration[10] and of (-)-**3c**, (-)-**3f** and their hydrogenated samples which were proved to have (R)-configuration. The determination of the configuration of (-)-**3c** and (-)-**3f** was made by the modified Mosher method reported by Kusumi and Kakisawa.[11] Reduction of the hydrogenated samples of (-)-**3c** and (-)-**3f** with $LiAlH_4$ gave two kinds of diastereomer which were separable by TLC and the relative configurations of which were determined by comparing the coupling constant in the ^{1}H NMR spectrum between the methine protons attached to the adjacent stereogenic carbon atoms. The (R^*,S^*)-diastereomers of the alcohols were converted to (R)- and (S)-MTPA esters and the configuration of the stereogenic carbon bearing hydroxyl group was determined to be S from the difference of the chemical shift of the esters. Therefore, the configuration of (-)-**3c** and (-)-**3f** is R.[12] According to the data described in Kagan's "Stereochemistry",[13] all (S)-ketones bearing a stereogenic carbon atom at the α-position, $R^3COCHR^1R^2$ (R^3=CH_3, R^1=Ph, R^2=CH_3, C_2H_5, C_3H_7, i-C_3H_5, C_4H_9; R^3=CH_3, R^1=$PhCH_2$, R^2=CH_3; R^3=C_2H_5, R^1=Ph, R^2=CH_3, C_2H_5, C_3H_7; R^3=C_3H_7, R^1=Ph, R^2=CH_3, C_2H_5; R^3=C_3H_7, R^1=$PhCH_2$, R^2=CH_3; R^3=C_4H_9, R^1=Ph, R^2=CH_3; R^3=Ph, R^1=$PhCH_2$, R^2=CH_3; R^3=Ph, R^1=Ph, R^2=CH_3, C_2H_5, $CH_2CH(CH_3)_2$, $PhCH_2$), show a positive specific rotation at 589 nm in such various solvent as toluene, benzene, ether, ethanol and dioxane or in neat. To the signal in higher magnetic field of the two methyl signals separated by Eu(hfc)$_3$ was assigned the (R)-configuration based upon the separation mode of (-)-**3a**, (-)-**3b**, (-)-**3c** and (-)-**3f**.

As seen from Table 2, the enantiomeric excesses were generally high in the substrates in which the difference in bulkiness of the two substituents is large (Entries 1-6) and extremely high enantioselectivity was achieved in the reaction of methyl(1-methyl-1-phenylethyl)ketene (**1c**) (Entry 3). The enantiomeic excesses were relatively low and the configuration was reversed in Entries 7-9 compared to that in other cases (Entries 1-6, 10 and 11). The difference in enantioselectivity was presumed to be attributable to the E/Z ratio of the samarium enolate (**2**). In order to clarify the relationship between the enantioselectivity of the protonation and the E/Z selectivity of the samarium enolate formation, enol acetates were isolated by a reaction of the enolate with acetic anhydride and its configuration and diastereomeric excess (% de=E~Z/E+Z) were determined by ^{1}H NMR and 2D ^{1}H NOESY spectra. The signal of substituent cis to the phenyl group is known to be shifted to higher field owing to ring current effect,[14a,b] and so to the signal in higher magnetic field of two acetyl signals was assigned (Z)-configuration in the cases that phenyl or benzyl group were attached to the olefinic carbon of the enol acetates. When a single geometrical isomer was obtained, the configuration was confirmed by measurement of NOE

between cis substituents in 2D ^{1}H NOESY spectrum. The results were summarized in Table 3 together with the data on the enantioselectivity.

As seen from Table 3, in most cases (Entries 1-9) the enantioselectivity depends upon the E/Z selectivity of the enol acetates (**5**). The E/Z selectivity increases with increasing difference in bulkiness of

Table 3. E/Z Selectivity of the Samarium Enolate Formation and Enantioselectivity of Protonation of the Enolate by DHPEX.



Entry	Ketenes	5			3	
		Yield (%)	%de	(Config.)	%ee	(Config.)
1	1a	67	92	(*Z*)	91	(*R*)
2	1b	53	85	(*Z*)	84	(*R*)
3	1c	88	>98	(*Z*)	97	(*R*)
4	1d	71	>98	(*Z*)	94	(*R*)
5	1e	63	>98	(*Z*)	93	(*R*)
6	1f	61	>98	(*Z*)	91	(*R*)
7	1g	50	75	(*E*)	85	(*S*)
8	1h	53	29	(*E*)	29	(*S*)
9	1i	63	72	(*E*)	68	(*S*)
10	1j	68	>98	(*Z*)	48	(*R*)
11	1k	60	64	(*E*)	62	(*R*)

the two substituents of the ketene and thus the enantioselectivity also increases with it. Single geometrical isomers of the enol acetates were obtained in Entries 3-6, and the enantiomeric excesses were high in these cases. These results reveal that the enantiofaceselectivity of the protonation step is high (> 90% ee) even in the case of low product enantiomeric excess (Entries 8 and 9) and that (R)- and (S)-ketone were formed from (Z)- and (E)-enolate, respectively. In Entries 10 and 11, the E/Z selectivity is expected to increase owing to enhanced steric repulsion caused by the interaction between allylating species and α-hydrogen atom of the tetrahydronaphthyl ring or the two chlorine atoms of the phenyl ring of the ketenes and thus the enantioselectivity is also expected to increase. However, the enantioselectivity was low although single (Z)-isomer of the enol acetate was obtained in Entry 10. In Entry 11, the enantio- and E/Z selectivity were both reversed compared to those of other cases.

Based upon these results and Tidwell's theoretical consideration on nucleophilic addition of alkyllithium to ketene, the stereochemistry of the samarium enolate formation and the enantioselective protona-

tion is deduced as follows.

Tidwell and coworkers have reported that bond formation occurs between the HOMO of the alkyllithium and the LUMO of the ketene in the reaction. LUMO for ketene lies in the molecular plane and the nucleophilic attack takes place in the plane at the α-carbon of the ketene (Fig. 1). Therefore, the steric interaction between the approaching alkyllitium and the substituents on the ketene determines the preferred direction of attack and the effect is quite significant to give a single geometrical isomer of the enolate when the difference in bulkiness of the substituents is large enough. Furthermore, the enolate formed need not be the thermodynamically more stable, since the repulsion between the substituents and alkyl group of the alkyllithium is larger in the transition state than in the enolate.[14b,c]

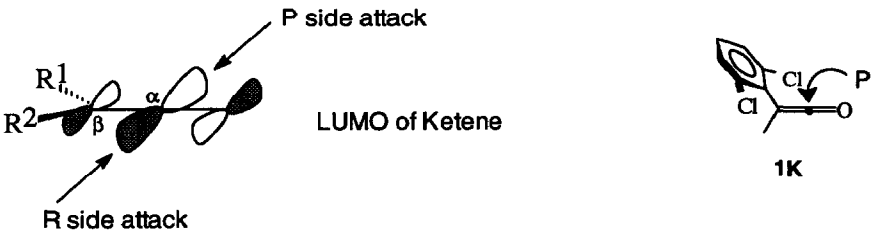


Fig. 1

Allylsamarium[15] is considered to be generated in the SmI_2 promoted cross-coupling reaction and to react with ketene via a simillar pathway as that of alkyllithium. Accordingly, (Z)-samarium enolate is formed preferentially by the R-side attack of the allylsamarium to the ketenes in which R^1 is the more bulky substituent than R^2 (Entries 1-6 and 10 in Table 3). On the other hand, P-side attack is preferred to give (E)-samarium enolate in the case of the ketenes in which R^2 is the more bulky substituent (Entries 7, 8 and 9) (Figs. 1 and 2). In Entry 11, the molecule may exist almost only in the conformation **1K** owing to large steric hindrance of the two chlorine atoms at the ortho positions. Therefore, the reversed E/Z selectivity can be explained by preferred P-side atack in the conformation **1K** or by directing effect[16] due to coordination of samarium ion to the chlorine atom (Figs. 1 and 3).

The protonation of the enolate takes place from the front side of the enolate plane in either the (Z)- or (E)-configuration when the structural formula is placed with O-Sm^{3+} group on the upper side of the paper as shown in Figs. 2 and 3 and thus results in the corresponding (R)- or (S)-ketones respectively in near 100% ee (Entries 1-9 in Table 2) (Fig. 2). From the result that low enantioselectivity was obtained in spite of the high E/Z selectivity in Entry 10 of Table 2, it is suggested that the low enantioselectivity is caused by the rigid planar conformation of the enolate plane at the side containing phenyl ring , and therefore, DHPEX recognizes one of the faces of the enolate plane containing C=C-OSm^{3+} and the substituent cis to O-Sm^{3+}, but the cis substituent is required to have vectorial component and certain bulkiness in the direction perpendicular to the enolate plane for the effective recognition of the face by DHPEX. The reversed enantio- and E/Z selectivity in Entry 11 of Table 2 indicates that the protonation occurs from back side of the enolate plane to provide (R)- or (S)-ketones from (E)- or (Z)-enolate, respectively in this case (Fig 3). However, it is neccesary to study further in order to clarify by what mechanism the reversed enantio- and E/Z selectivity is brought about in the reaction.

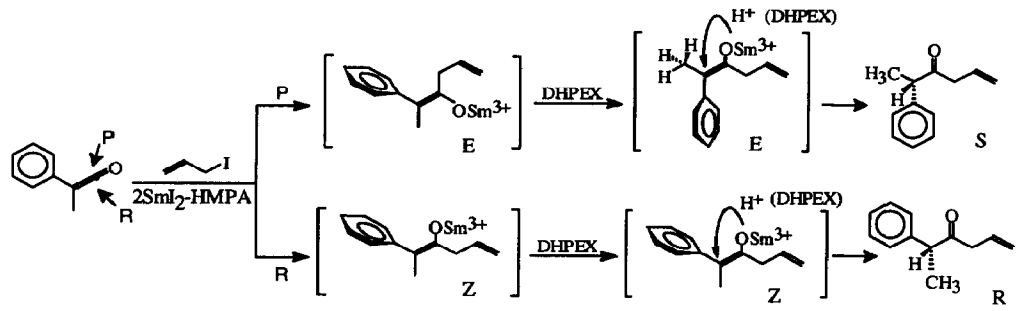


Fig. 2

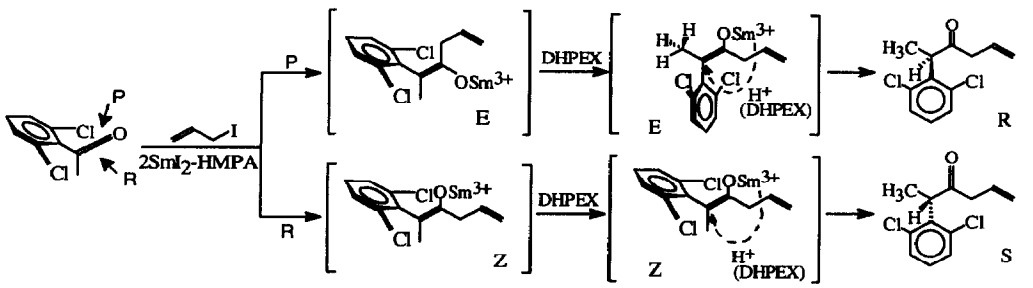


Fig. 3

From the fact that there exists the optimal values of DHPEX/Sm and HMPA/Sm, it is suggested that the enolate anion, tetradentate ligand DHPEX, HMPA and THF are coordinated to the samarium ion in the protonating transition state to enhance the steric control resulting in the high enantioselectivity. High oxophilicity and high coordination number of samarium ion[17] may play an important role in this stage.

Experimental Section

General. The melting point was determined by a Yanagimoto micro-melting point apparatus and was uncorrected. The IR spectra were recorded on a Perkin-Elmer 1720-X FT-IR spectrometer. The ^1H NMR spectra were obtained on a JEOL-FX 200 and JEOL a-400 spectrometer ($CDCl_3$). The 2D ^1H NOESY spectra were obtained on a JEOL a-400 spectrometer ($CDCl_3$). The optical rotations were measured with a Perkin Elmer 241 polarimeter and the CD spectra were recorded on a JASCO J-40C spectrometer. Mass spectra were measured on a Hitachi M-2500 double focusing mass spectrometer. HPLC analysis was performed with Waters M-6000A flow system and MODEL 440 detector using DAICEL Chiralcel OB' and OD column. Preparative TLCs were run on Wakogel B-5F and column chromatography was performed using Wakogel C-300.

Materials. Tetrahydrofuran (THF) was distilled prior to use from sodium benzophenone ketyl under

argon. Hexamethylphosphoric triamide (HMPA) was distilled from CaH_2. Toluene and mesitylene were distilled and dried with sodium. Acetic anhydride was purified by stirring with sodium for a week at room temperature under argon and then distilling under reduced pressure.[18] Allyl iodide was purified by distillation. Samarium iodide (II) solution in THF (0.1M) was prepared from samarium and diiodoethane according to Kagan's method.[19] Tris[3-(heptafluoropropylhydroxymethylene)-(+)-camphorato]europium(III) ($Eu(hfc)_3$, Aldrich) was used as a chiral shift reagent. Methylphenylketene (**1a**),[14b] ethylphenylketene (**1b**),[14b] (p-chlorophenyl)isopropylketene (**1g**),[14b] benzylethylketene (**1h**),[20] benzylisopropylketene (**1i**),[20] and phenyl-α,o-trimethyleneketene (**1j**)[21] were prepared according to literatures. Other ketenes were prepared by dehydrochlorination of the corresponding acylchlorides with triethylamine or with 1,4-diazabicyclo[2,2,2]octane (DABCO) in the case of t-butylmethylketene (**1e**). The acyl chlorides were obtained from the corresponding carboxylic acids which were prepared by C-2 methylation[22] of lithium ester enolate of the precursor carboxylic acids esters. 2,6-Dichlorophenylacetic acid (Aldrich) and ethyl t-butylacetate (Tokyo Kasei) were commercially avairable. 3-Methyl-3-phenylbutanoic acid,[23] 3-benzyl-3-methylbutanoic acid[23] and 3,3-dimethylheptanoic acid[24] were prepared according to literatures. The ketenes were stored under argon in a refrigerator.

Methyl(1-methyl-1-phenylethyl)ketene (1c). *Ethyl 3-methyl-3-phenylbutanoate (1c-1)* was obtained by the reaction of the corresponding acid (16 g, 90 mmol) with ethanol (60 ml) in the presence of p-toluenesulphonic acid monohydrate (1.2 g, 6.3 mmol) in benzene (170 ml) by azeotropic evaporation and dehydration using Soxhlet's extractor type column packed with MS-3A for 17 h. After usual work up, the crude product was distilled under reduced presure (113-117 °C/8 mmHg) to give oil (15.3 g, 83%): ^{1}H NMR δ=1.07 (3H, t, J=7.1Hz, $CH_2C\underline{H}_3$), 1.46 (6H, s, $PhC(C\underline{H}_3)_2$), 2.60 (2H, s, $C\underline{H}_2COOC_2H_5$), 3.97 (2H, q, J=7.1Hz, $C\underline{H}_2CH_3$), 7.17-7.40 (5H, m, Ph).

Ethyl 2,3-dimethyl-3-phenylbutanoate (1c-2) was prepared by C-2 methylation[22] of *(1c-1)* (117-122 °C/8 mmHg, 93%): ^{1}H NMR δ=0.92 (3H, d, J=7.1Hz, $CHC\underline{H}_3$), 1.11 (3H, t, J=7.1Hz, $CH_2C\underline{H}_3$), 1.38 (6H, s, $PhC(C\underline{H}_3)_2$), 2.77 (1H, q, J=7.1Hz, $C\underline{H}CH_3$), 3.99 (2H, q, J=7.1Hz, $C\underline{H}_2CH_3$), 7.17-7.37 (5H, m, Ph).

2,3-Dimethyl-3-phenylbutanoic acid (1c-3) was prepared by saponification of *(1c-2)* (8.2g, 32 mmol) with potassium hydroxide (6.5g, 115 mmol) in ethanol (50 ml) under reflux for 13 h. After removing the solvent, water was added and extracted the unreacted starting materials with ether. The water layer was acidified with 3N hydrochloric acid and extracted with ether. The ether layer was dried over anhydrous Na_2SO_4 and removing the solvent gave almost pure crystalline material (6.5 g, 91%): ^{1}H NMR δ=0.94 (3H, d, J=7.1Hz, $CHC\underline{H}_3$), 1.41 (3H, s, $PhC(C\underline{H}_3)_2$), 1.44 (3H, s, $PhC(C\underline{H}_3)_2$), 2.80 (1H, q, J=7.1Hz, $C\underline{H}CH_3$), 7.16-7.40 (5H, m, Ph).

2,3-Dimethyl-3-phenylbutanoyl chloride (1c-4) was obtained by chlorination of *(1c-3)* (6g, 31 mmol) with thionyl chloride (12 ml, 165 ml) at room temperature for 1 h and under reflux for 2 h. After removing excess thionyl chloride, distillation under reduced pressure gave oil (95-97 °C/8.5 mmHg, 5.6 g, 85%): ^{1}H NMR δ=1.15 (3H, d, J=7.1Hz, $CHC\underline{H}_3$), 1.42 (3H, s, $PhC(C\underline{H}_3)_2$), 1.50 (3H, s, $PhC(C\underline{H}_3)_2$), 3.31 (1H, q, J=7.1Hz, $C\underline{H}CH_3$), 7.19-7.38 (5H, m, Ph).

The ketene (**1c**) was prepared by dehydrochlorination of *(1c-4)* (3.6 g, 17 mmol) with triethylamine (7.1 ml, 51 mmol) in toluene (20 ml) under reflux and argon atmosphere for 32 h. After filtration of triethylamine hydrochloride and concentratin of the filtrate under argon, the residue was distilled under re-

duced pressure to give oil (60-70 °C/1.5 mmHg, 1.4 g, 46%): ^{1}H NMR δ=1.41 (3H, s, =C-C$\underline{H}_3$), 1.47 (6H, s, PhC(C$\underline{H}_3$)$_2$), 7.22-7.41 (5H, m, Ph); IR (neat) 2104 cm^{-1} (C=C=O).

(1,1-Dimethyl-2-phenylethyl)methylketene (1d). This was prepared from 3,3-dimethyl-4-phenylbutanoic acid by the procedure similar to that of (**1c**) and obtained from 2,3,3-trimethyl-4-phenylbutanoylchloride in 25% yield (71-72 °C/1.5 mmHg): ^{1}H NMR δ=1.03 (3H, s, PhC(C$\underline{H}_3$)$_2$), 1.04 (3H, s, PhC(C$\underline{H}_3$)$_2$), 1.66 (3H, s, =C-C$\underline{H}_3$), 2.61 (2H, s, PhC$\underline{H}_2$), 7.08-7.27 (5H, m, Ph); IR (neat) 2104 cm^{-1} (C=C=O).

t-Butylmethylketene (1e). 2,3,3-trimethylbutanoyl chloride (2.2 g, 14 mmol) which was prepared from ethyl t-butylacetate by the procedure similar to that of *(1c-4)* was dehydrochlorinated by DABCO (1.62 g, 14 mmol) in mesitylene (20 ml) under argon atmosphere at 80 °C for 3.5 h. After filtration of DABCO hydrochloride, the filtrate was distilled at atmospheric pressure under argon. The main fraction (65-120 °C) contains almost equal amount of the ketene and mesitylene (about 0.55 g:0.80g): ^{1}H NMR δ=1.08 (9H, s, (C$\underline{H}_3$)$_3$C), 1.57 (3H, s,=C-C$\underline{H}_3$); IR (the mixture of the ketene and mesitylene) 2105 cm^{-1} (C=C=O).

(1,1-Dimethylpentyl)methylketene (1f). This was prepared from 1,3-dimethylheptanoic acid by the procedure similar to that of (**1c**) and obtained from 2,3,3-trimethylheptanoyl chloride in 22% yield (65-70 °C/1.5 mmHg): ^{1}H NMR δ=0.90 (3H, m, C$\underline{H}_3$CH$_2$CH$_2$CH$_2$), 1.04 (6H, s, C(C$\underline{H}_3$)$_2$), 1.10-1.36 (6H, m, CH$_3$C$\underline{H}_2$C$\underline{H}_2$C$\underline{H}_2$), 1.53 (3H, s, =C-C$\underline{H}_3$); IR (neat) 2104 cm^{-1} (C=C=O).

2,6-Dichlorophenylmethylketene (1k). This was prepared from 2,6-dichlorophenylacetic acid by the procedure similar to that of (**1c**) and obtained from 2-(2',6'-dichlorophenyl)propanoyl chloride in 17% yield (62-63 °C/5 mmHg): ^{1}H NMR δ=2.00 (3H, s, C$\underline{H}_3$), 6.92-7.39 (3H, m, C$_6$H$_3$); IR (neat) 2119 cm^{-1} (C=C=O).

α,α'-Bis[(S)-2-tetrahydropyranyloxy-2-phenylethyl]-o-xylenedioxide (8). To a suspension of sodium hydride (1.5 g, 63 mmol) in THF (100 ml) a solution of (S)-2-tetrhydropyranyloxy-2-phenylethanol (7) (12.3 g, 55 mmol) in THF (50 ml) was added at 0 °C and the reaction mixture was stirred for 30 min at room temperature under argon. To the solution was added a solution of α,α'-o-xylyldibromide (7.3 g, 28 mmol) in THF (50 ml) and stirred overnight. After refluxing for 1 h, water (1 ml) was added to the solution at room temperature and the solution was extracted with ether. The ether layer was washed twice with brine and dried over anhydrous Na_2SO_4. After removing the solvent, the residue was purified by column chromatography (hexane-ethyl acetate) to give oily material (11.8 g, 78%): ^{1}H NMR δ=1.24-2.02 (12H, m, THP), 3.18-3.76 (8H, m, C$\underline{H}_2$O), 3.90-4.10 (2H, m, OC$\underline{H}$O), 4.36-4.64 (4H, m, C$_6$H$_4$(C$\underline{H}_2$)$_2$), 4.78-5.02 (2H, m, PhC$\underline{H}$), 7.10-7.38 (14H, m, Ph, C$_6$H$_4$).

Bis(R)-isomer was prepared by the same procedure and (R,S)-diastereomer was prepared by stepwise reaction of (R)- and (S)-2-tetrahydropyranyloxy-2-phenylethanol with α,α'-o-xylyldibromide.

α,α'-Di[(S)-2-hydroxy-2-phenylethyl]-o-xylenedioxide (DHPEX). To a solution of α,α'-bis[(S)-2-tetrahydropyranyloxy-2-phenylethyl]-o-xylenedioxide (11.0 g, 20 mmol) in methanol (200 ml) was added p-toluenesulphonic acid monohydrate (1.1 g, 5.8 mmol) and stirred for 40 min at room temperature. After removing methanol, 5% sodium carbonate solution (50 ml) was added to the residue and the mixture was extracted with ether. The ether layer was dried over anhydrous Na_2SO_4 and then concentrated in vacuo to give oily material. This was purified by column chromatography (hexane-ethyl

acetate) to afford oil which gradually crystallized (5.52 g, 73%). Enantiomeric purity of the product was determined to be 99.98% by HPLC using DAICEL Chiralcel OJ (hexane:2-propanol=7:3). $[\alpha]_D^{17}$ +87.0 (c 1.057, $CHCl_3$). Mp. 58.0-59.0 °C. ^{1}H NMR δ=3.45-3.54 (2H, dd, J=8.8Hz, 9.8Hz, OC$\underline{H}_2$CHOH), 3.61-3.67 (2H, dd, J=3.2Hz, 9.8Hz, OC$\underline{H}_2$CHOH), 3.90 (2H, s, O$\underline{H}$), 4.57 (2H, d, J=11.6Hz, PhC$\underline{H}_2$O), 4.67 (2H, d, J=11.6Hz, PhC$\underline{H}_2$O), 4.89 (2H, dd, J=3.2Hz, 8.8Hz, $CH_2C\underline{H}$OH), 7.23-7.33 (14H, m, Ph, C_6H_4). IR (KBr) 3312 cm^{-1} (OH), 1092 cm^{-1} (C-O-C), 754 and 701 cm^{-1} (Ph). Found: C, 76.17%; H, 6.92%. Calcd for $C_{24}H_{26}O_4$: C, 76.24%, H, 6.96%.

(R,R)-DHPEX and (R,S)-DHPEX were prepared by the procedure similar to that of DHPEX: (R,R)-DHPEX, $[\alpha]_D^{22}$ -82.9 (c 1.083, $CHCl_3$) (76%).

Enantioselective protonation of samarium enolate by DHPEX. For a typical example, the procedure of Entry 3 in Table 2 is described as follows: To a solution of (**1c**) (77.5 mg, 0.44 mmol), allyl iodide (290.7 mg, 1.7 mmol) and HMPA (149.2 mg, 0.83 mmol) in THF (2 ml) was added a 0.1M solution of SmI_2 (10.7 ml, 1.07 mmol) with stirring under argon atmosphere at room temperature. After 2 min, the solution was cooled to -78 °C and then to the solution was added a solution of DHPEX (253.0 mg, 0.67 mmol) in THF (2 ml). The reaction was continued for 30 min at the temperature followed by allowing the reaction solution to stand at room temperature for 40 min. The reaction was quenched with 0.1N hydrochloric acid (4 ml) and the reaction mixture was extracted with ether. The ether layer was washed successively with brine, 2% $Na_2S_2O_3$ solution and brine, and then dried over anhydrous Na_2SO_4. After removing the solvent, the crude product was purified by preparative TLC (hexane:ethyl acetate=50:1) to give 5,6-dimethyl-6-phenyl-1-hepten-4-one (**3c**) containing about 9% of its α,β-unsaturated isomer (**4c**) (oil, 62.9 mg, 65%). The product was hydrgenated over palladium on charcoal and purified by preparative TLC (hexane:ethyl acetate=10:1). Enantiomeric excess of the sample was determined to be 97% by HPLC analysis using DAICEL Chiralcel OD column (sampling solvent,hexane:ether=10:1; hexane as eluate). The β,γ- and α,β-isomers were also isolated by TLC independently (hexane:ethyl acetate=50:1). The β,γ-isomer ($[\alpha]_D^{20}$ -194 (c 0.758, toluene)) was analyzed by ^{1}H NMR spectrum to be almost equal enantiomeric excess as that determined by HPLC analysis. Each signal of 5-methyl and 6,6-dimethyl was completely separeted in the presence of $Eu(hfc)_3$ and the enantiomeric excess was calculated from the integration of the signals. The configuration was determined to be R by the method described in Ref. 12. Therefore, to the larger ones in higher field of the signal pairs were assigned R-configuration and the separation mode was the same as that of (-)-**3a** and (-)-**3b** which have (R)-configuration.[10] The CD spectrum at 240-340 nm of the hydrogenated sample ($[\alpha]_D^{19}$ -130 (c 0.236, ether)) exhibited a negative Cotton effect (λext 295 nm Δε -2.4). DHPEX was recovered in 96% and confirmed to be 100% ee by HPLC analysis. The spectroscopic data of (**3c**) were as follows: ^{1}H NMR δ=0.99 (3H, d, J=7.1Hz, CHC$\underline{H}_3$), 1.37 (3H, s, PhC(C$\underline{H}_3$)$_2$-), 1.39 (3H, s, PhC(C$\underline{H}_3$)$_2$-), 2.56 (1H, dd, J=17Hz, 7.1Hz, C$\underline{H}_2$CH=CH_2), 2.78 (1H, dd, J=17Hz, 6.8Hz, C$\underline{H}_2$CH=CH_2), 2.94 (1H, q, J=7.1Hz, C$\underline{H}$$CH_3$), 4.85 (1H, bd, J=17Hz, CH=C$\underline{H}_2$), 5.04 (1H, bd, J=9.5Hz, CH=C$\underline{H}_2$), 5.59-5.80 (1H, m, C$\underline{H}$=CH_2), 7.15-7.37 (5H, m, Ph). IR (neat) 1712 cm^{-1} (C=O). HRMS Found:m/z 216.1505 Calcd for $C_{15}H_{20}O$:M, 216.1513.

(R)-5-Phenyl-1-hexen-4-one ((R)-3a). $[\alpha]_D^{20}$ -283 (c 0.570, toluene). ^{1}H NMR δ=1.39 (3H, d, J=7.1Hz, CHC$\underline{H}_3$), 3.11 (2H, bd, J=7.1Hz, C$\underline{H}_2$CH=CH_2), 3.81 (1H, q, J=7.1Hz, C$\underline{H}$$CH_3$), 4.94-5.13 (2H, m, CH=C$\underline{H}_2$), 5.73-5.94 (1H, m, C$\underline{H}$=CH_2), 7.18-7.38 (5H, m, Ph). IR (neat) 1717 cm^{-1} (C=O).

HRMS Found:m/z 174.1010 Calcd for $C_{12}H_{14}O$:M, 174.1045. ^1H NMR (Eu(hfc)$_3$):(-)-Enantiomer has (R)-configuratioin and so to the larger signal of 6-methyl proton in higher magnetic field was assigned R-configuration. HPLC (hydrogenated sample):DAICEL Chiralcel OB' column (hexane); 91% ee. CD (hydrogenated sample $[\alpha]_D^{20}$ -234 (c 0.281, toluene), ether):λext 292 nm Δε -5.5.

(R)-5-Phenyl-1-hepten-4-one ((R)-3b). $[\alpha]_D^{17}$ -287 (c 0.350, toluene). ^1H NMR δ=0.82 (3H, t, J=7.3Hz, $CH_2C\underline{H}_3$), 1.59-1.82 (1H, m, $C\underline{H}_2CH_3$), 1.96-2.17 (1H, m, $C\underline{H}_2CH_3$), 3.11 (2H, d, J=6.8Hz, $C\underline{H}_2CH{=}CH_2$), 3.58 (1H, t, J=7.3Hz, PhC$\underline{H}$CO), 4.97-5.14 (2H, m, CH=C$\underline{H}_2$), 5.73-5.93 (1H, m, C$\underline{H}$=CH$_2$), 7.20-7.37 (5H, m, Ph). IR (neat) 1714 cm^{-1}. HRMS Found:m/z 188.1172 Calcd for $C_{13}H_{16}O$:M, 188.1202. ^1H NMR (Eu(hfc)$_3$):(-)-Enantiomer has (R)-configuration and so to the larger signal of 7-methyl proton in higher magnetic field was assigned R-configuration. HPLC (hydrogenated sample):DAICEL Chiralcel OB' (hexane); 84% ee. CD (hydrogenated sample $[\alpha]_D^{19}$ -264 (c 0.480, toluene), ether):λext 292 nm Δε -6.8.

(R)-7-Phenyl-5,6,6-trimethyl-1- and -2-hepten-4-one ((R)-3d and (R)-4d). $[\alpha]_D^{19}$ -107 (c 0.565, toluene). ^1H NMR δ=0.90 (3H, s, PhC(C$\underline{H}_3$)$_2$), 0.92 (3H, s, PhC(C$\underline{H}_3$)$_2$), 1.13 (3H, d, J=7.1Hz, CHC$\underline{H}_3$), 2.53-2.68 (3H, m, C$\underline{H}$CH$_3$, PhC$\underline{H}_2$), 3.18 (2H, bd, J=6.8Hz, C$\underline{H}_2$CH=CH$_2$), 5.03-5.19 (2H, m, CH=C$\underline{H}_2$), 5.81-6.01 (1H, m, C$\underline{H}$=CH$_2$), 7.09-7.31 (5H, m, Ph). IR (neat) 1712 cm^{-1} (C=O). HRMS Found:m/z 230.1618 Calcd for $C_{16}H_{22}O$:M, 230.1669. ^1H NMR (Eu(hfc)$_3$):To the larger signal of 5-methyl proton in higher magnetic field was assigned R-configuration. HPLC (hydrgenated sample):DAICEL Chiralcel OD (sampling solvent; hexane:ether=10:1, hexane); 94% ee. CD spectrum (hydrogenated sample $[\alpha]_D^{19}$ -66 (c 0.415, ether), ether):λext 295 nm Δε -1.2.

(R)-4,5,5-Trimethyl-1-hepten-4-one ((R)-3e). $[\alpha]_D^{23}$ -386 (c 1.350, toluene). ^1H NMR δ=0.88 (9H, s, (C$\underline{H}_3$)$_3$C), 0.95 (3H, d, J=7.1Hz, CHC$\underline{H}_3$), 2.43 (1H, q, J=7.1Hz, C$\underline{H}$CH$_3$), 3.14 (2H, bd, J=7.1Hz, C$\underline{H}_2$CH=CH$_2$), 4.99-5.13 (2H, m, CH=C$\underline{H}_2$), 5.74-6.95 (1H, m, C$\underline{H}$=CH$_2$). IR (neat) 1731 cm^{-1} (C=O). HRMS Found:m/z 154.1407 Calcd for $C_{10}H_{18}O$:M, 154.1357. ^1H NMR (Eu(hfc)$_3$):To the larger signal of 5-methyl proton in higher magnetic field was assigned R-configuration; 93% ee. CD (ether)^{25}:λext 300 nm Δε -1.7.

(R)-5,6,6-Trimethyl-1-decen-4-one ((R)-3f). $[\alpha]_D^{19}$ -118 (c 0.830, toluene). ^1H NMR δ=0.78-1.00 (3H, m, C$\underline{H}_3$CH$_2$CH$_2$CH$_2$), 0.83 (3H, s, (C$\underline{H}_3$)$_2$C), 0.85 (3H, s, (C$\underline{H}_3$)$_2$C), 0.93 (3H, d, J=7.1Hz, CHC$\underline{H}_3$), 1.00-1.40 (6H, m, CH$_3$C$\underline{H}_2$C$\underline{H}_2$C$\underline{H}_2$), 2.51 (1H, q, J=7.1Hz, C$\underline{H}$CH$_3$), 3.14 (2H, bd, J=6.8Hz, C$\underline{H}_2$CH=CH$_2$), 4.94-5.12 (2H, m, CH=C$\underline{H}_2$), 5.70-5.94 (1H, m, C$\underline{H}$=CH$_2$). IR (neat) 1713 cm^{-1} (C=O). HRMS Found:m/z 196.1847 Calcd for $C_{13}H_{24}O$:M, 196.1826. The configuration was determined to be R by the method described in Ref. 12. ^1H NMR (Eu(hfc)$_3$):To the larger signal of 5-methyl proton in higher magnetic field was assigned R-configuration; 91% ee. CD (hydrogenated sample $[\alpha]_D^{18}$ -47.3 (c 0.275, ether), ether):λext 295 nm Δε -0.75.

(S)-5-(5'-Chlorophenyl)-6-methyl-1-hepten-4-one ((S)-3g). $[\alpha]_D^{24}$ +210 (c 0.508, toluene). ^1H NMR δ=0.69 (3H, d, J=6.8Hz, CH(C$\underline{H}_3$)$_2$), 0.96 (3H, d, J=6.4Hz, CH(C$\underline{H}_3$)$_2$), 2.27-2.45 (1H, m, C$\underline{H}$(CH$_3$)$_2$), 3.13 (2H, bd, J=7.1Hz, C$\underline{H}_2$CH=CH$_2$), 3.35 (1H, d, J=10.5Hz, C$\underline{H}$CH(CH$_3$)$_2$), 5.00-5.18 (2H, m, CH=C$\underline{H}_2$), 5.70-5.91 (1H, m, C$\underline{H}$=CH$_2$), 7.16 (2H, d, J=8.5Hz, 2'H), 7.28 (2H, d, J=8.5Hz, 3'H). IR (neat) 1715 cm^{-1} (C=O). HRMS Found:m/z 236.0897 Calcd for $C_{14}H_{17}ClO$:M, 236.0969. ^1H NMR (Eu(hfc)$_3$):To the larger signal of 7-methyl proton in lower magnetic field was assigned S-configuration;

85% ee. CD (hydrogenated sample $[\alpha]_D^{18}$ +198 (c 0.635, toluene), ether):λext 293 nm Δε +5.75.

(S)-5-Benzyl-1- and -2-hepten-4-one ((S)-3h and (S)-4h). $[\alpha]_D^{24}$ +23.0 (c 0.608, toluene). ^{1}H NMR : β,γ-isomer ((S)-**3h**) δ=0.92 (3H, t, J=7.3Hz, $CH_2C\underline{H}_3$), 1.44-1.76 (2H, m, $C\underline{H}_2CH_3$), 2.64-3.04 (3H, m, $PhC\underline{H}_2C\underline{H}$, $C\underline{H}_2CH{=}CH_2$), 4.94-5.12 (2H, m, $CH{=}C\underline{H}_2$), 5.68-5.90 (1H, m, $C\underline{H}{=}CH_2$), 7.12-7.32 (5H, m, Ph); α,β-isomer ((S)-**4h**) δ=0.90 (3H, t, J=7.2Hz, $CH_2C\underline{H}_3$), 1.44-1.76 (2H, m, $C\underline{H}_2CH_3$), 1.84 (3H, dd, J=6.4Hz, 1.6Hz, $CH{=}CHC\underline{H}_3$), 2.60-3.00 (3H, m, $PhC\underline{H}_2C\underline{H}$), 6.12 (1H, dq, J=15Hz, 1.6Hz, $C\underline{H}{=}CHCH_3$), 6.80 (1H, dq, J=15Hz, 6.4Hz, $CH{=}C\underline{H}CH_3$), 7.00-7.32 (5H, m, Ph). IR (neat, β,γ-isomer) 1713 cm^{-1}. HRMS Found:m/z 202.1348 Calcd for $C_{14}H_{18}O$:M, 202.1356. ^{1}H NMR (Eu(hfc)$_3$, β,γ-isomer):To the larger signal of 7-methyl proton in lower magnetic field was assigned S-configuration. HPLC (hydrogenated sample):DAICEL Chiralcel OB' (hexane); 29% ee. CD (hydrogenated sample $[\alpha]_D^{24}$ +13.5 (c 0.185, ether), ether):λext 293 nm Δε +2.7.

(S)-5-Benzyl-6-methyl-1- and -2-hepten-4-one ((S)-3i and (S)-4i). $[\alpha]_D^{23}$ +46.5 (c 1.220, toluene). ^{1}H NMR: β,γ-isomer ((S)-**3i**) δ=0.98 (3H, d, J=7.2Hz, $CH(C\underline{H}_3)_2$), 1.02 (3H, d, J=7.2Hz, $CH(C\underline{H}_3)_2$), 1.98 (1H, m, J=7.2Hz, $C\underline{H}(CH_3)_2$), 2.60-3.02 (5H, m, $PhC\underline{H}_2C\underline{H}$, $C\underline{H}_2CH{=}CH_2$), 4.88 (1H, d, J=17Hz, $CH{=}C\underline{H}_2$), 5.04 (1H, d, J=9.6Hz, $CH{=}C\underline{H}_2$), 5.58-5.78 (1H, m, $C\underline{H}{=}CH_2$), 7.10-7.30 (5H, m, Ph); α,β-isomer ((S)-**4i**) d=0.98 (3H, d, J=7.2Hz, $CH(C\underline{H}_3)_2$), 1.00 (3H, d, J=7.2Hz, $CH(C\underline{H}_3)_2$), 1.78 (3H, dd, J=7.3Hz, 1.6Hz, $CH{=}CHC\underline{H}_3$), 2.00 (1H, m, J=7.2Hz, $C\underline{H}(CH_3)_2$), 2.76-2.96 (3H, m, $PhC\underline{H}_2C\underline{H}$), 6.04 (1H, dt, J=16Hz, 1.6Hz, $C\underline{H}{=}CHCH_3$), 6.66 (1H, dq, J=16Hz, 7.3Hz, $CH{=}C\underline{H}CH_3$), 7.08-7.30 (5H, m, Ph). IR (neat, β,γ-isomer) 1713 cm^{-1} (C=O). HRMS Found:m/z 202.1348 Calcd for $C_{14}H_{18}O$:M, 202.1356. ^{1}H NMR (Eu(hfc)$_3$, β,γ-isomer):To the larger signal of 7-methyl proton in lower magnetic field was assigned S-configuration; 68% ee. CD (hydrogenated sample $[\alpha]_D^{19}$ +11.8° (c 0.212, ether), ether):λext 293 nm Δε -0.5.[26]

(R)-4-[1'-(1',2',3',4'-tetrahydronaphthyl)-1- and -2-buten-4-one ((R)-3j and (R)-4j). $[\alpha]_D^{15}$ -31.0 (c 1.666, toluene). ^{1}H NMR: β,γ-isomer ((R)-**3j**) δ=1.72-2.06 (4H, m, 2',3'-$C\underline{H}_2C\underline{H}_2$), 2.80 (2H, m, 4'-$CH_2$), 3.21 (2H, bd, J=6.8Hz, $C\underline{H}_2CH{=}CH_2$), 3.97 (1H, t, J=6.4Hz, 1'-CH), 5.02-5.19 (2H, m, $CH{=}C\underline{H}_2$), 5.81-5.99 (1H, m, $C\underline{H}{=}CH_2$), 6.91-7.17 (4H, m, C_6H_4); α,β-isomer ((R)-**4j**) δ=1.85 (3H, dd, J=6.8Hz, 1.7Hz, $CH{=}CHC\underline{H}_3$), 1.72-2.06 (4H, m, 2',3'-$C\underline{H}_2C\underline{H}_2$), 2.80 (2H, m, 4'-$CH_2$), 3.19 (1H, t, J=6.4Hz, 1'-CH), 6.15 (1H, dq, J=16Hz, 1.5Hz, $C\underline{H}{=}CHCH_3$), 6.94 (1H, dq, J=16Hz, 6.8Hz, $CH{=}C\underline{H}CH_3$), 6.91-7.17 (4H, m, C_6H_4). IR (neat, β,γ-isomer) 1712 cm^{-1}. HRMS (hydrogenated sample) Found:m/z 202.1421 Calcd for $C_{14}H_{18}O$:M, 202.1357. HPLC (hydrogenated sample):DAICEL Chiralcel OD (hexane); 75% ee. CD (hydrogenated sample $[\alpha]_D^{19}$ -10.3 (c 0.505, ether), ether):λext 273 and 294 nm Δε -0.75 and -0.35, respectively.

(R)-5-(2',6'-dichlorophenyl)-1-hexen-4-one ((R)-3k). $[\alpha]_D^{19}$ -111 (c 0.797, toluene). ^{1}H NMR δ=1.46 (3H, d, J=6.8Hz, $CHC\underline{H}_3$), 3.07 (2H, bd, J=6.6Hz, $C\underline{H}_2CH{=}CH_2$), 4.33 (1H, q, J=6.8Hz, $C\underline{H}CH_3$), 4.98 (1H, bd, J=17Hz, $CH{=}C\underline{H}_2$), 5.12 (1H, bd, J=11Hz, $CH{=}C\underline{H}_2$), 5.79-6.00 (1H, m, $C\underline{H}{=}CH_2$), 7.13-7.37 (5H, m, Ph). IR (neat) 1719 cm^{-1} (C=O). HRMS (hydrogenated sample) Found:m/z 244.0316 Calcd for $C_{12}H_{14}Cl_2O$:M, 244.0420. ^{1}H NMR (Eu(hfc)$_3$):To the larger signal of 6-methyl proton in higher magnetic field was assigned R-configuration. HPLC (hydrogenated sample):DAICEL Chiralcel OB' (hexane); 79% ee. CD (hydrogenated sample $[\alpha]_D^{19}$ -110 (c 0.990, ether), ether):λext 290 nm Δε -4.80.

Isolation of enol acetates. For a typical example, the procedure of Entry 3 in Table 3 is described as follows: to a solution of (1c) (80 mg, 0.46 mmol), allyl iodide (239 mg, 1.42 mmol) and HMPA (124 mg, 0.69 mmol) in THF (2 ml) was added a 0.1M solution of SmI_2 in THF (10 ml, 1.0 mmol) under argon with stirring at room temperature. After stirring for 5 min, acetic anhydride (1 ml) was added to the solution and the reaction was continued for 2 h at room temperature. The reaction was quenched with 3N hydrochloric acid (4 ml) and the mixture was extracted with ether. The ether layer was washed successively with brine, 2% $Na_2S_2O_3$ solution and brine, and then dried over anhydrous Na_2SO_4. After removing the solvent, the crude product was purified by preparative TLC on silicagel (hexane:ethyl acetate=10:1) to give the enol acetate (5c) (oil, 70 mg, 75%). ^{1}H NMR (400 MHz) δ=1.42 (6H, s, $PhC(C\underline{H}_3)_2$), 1.59 (3H, s, $C\underline{H}_3C$=C), 1.72 (3H, s, $OCOC\underline{H}_3$), 3.04 (2H, d, J=6.3Hz, $C\underline{H}_2CH$=CH_2), 5.00-5.08 (2H, m, CH=$C\underline{H}_2$), 5.68-5.81 (1H, m, $C\underline{H}$=CH_2), 7.11-7.28 (5H, m, Ph). No signal other than these were observed in the ^{1}H NMR spectrum and NOE was observed between 5-methyl (δ=1.59) and 3-methylene (δ=3.04) signals in 2D ^{1}H NOESY spectrum. Therefore, it was concluded that single geometrical isomer was obtained and its configuration is Z. IR (neat) 1750 cm^{-1} (ester C=O). HRMS Found:m/z 258.1596 Calcd for $C_{17}H_{22}O_2$:M, 258.1617.

(Z)-4-Acetoxy-5-phenyl-1,4-hexadiene ((Z)-5a). ^{1}H NMR (400 MHz) δ=1.84 (3H, s, $OCOC\underline{H}_3$), 2.03 (3H, s, $C\underline{H}_3C$=C), 3.17 (2H, d, J=6.3Hz, $C\underline{H}_2CH$=CH_2). 5.07-5.21 (2H, m, CH=$C\underline{H}_2$), 5.75-5.92 (1H, m, $C\underline{H}$=CH_2), 7.17-7.37 (5H, m, Ph). IR (neat) 1750 cm^{-1} (ester C=O). HRMS Found:m/z 216.1101 Calcd for $C_{14}H_{16}O_2$:M, 216.1149.

(E)-4-Acetoxy-5-phenyl-1,4-hexadiene ((E)-5a). ^{1}H NMR (400 MHz) δ=1.89 (3H, s, $C\underline{H}_3C$=C), 2.19 (3H, s, $OCOC\underline{H}_3$), 2.95 (2H, d, J=8.0Hz, $C\underline{H}_2CH$=CH_2), 5.01-5.06 (2H, m, CH=$C\underline{H}_2$), 5.71-5.78 (1H, m, $C\underline{H}$=CH_2), 7.23-7.35 (5H, m, Ph). IR (neat) 1750 cm^{-1} (ester C=O). HRMS Found:m/z 216.1094 Calcd for $C_{14}H_{16}O_2$:M, 216.1149.

(Z)-4-Acetoxy-5-phenyl-1,4-heptadiene ((Z)-5b). ^{1}H NMR (400 MHz) δ=0.94 (3H, t, J=7.3Hz, $C\underline{H}_3CH_2$), 1.77 (3H, s, $OCOC\underline{H}_3$), 2.41 (2H, q, J=7.3Hz, $CH_3C\underline{H}_2$), 3.17 (2H, d, J=6.3Hz, $C\underline{H}_2CH$=CH_2), 5.06-5.21 (2H, m, CH=$C\underline{H}_2$), 5.76-5.96 (1H, m, $C\underline{H}$=CH_2), 7.12-7.33 (5H, m, Ph). IR (neat) 1752 cm^{-1} (ester C=O). HRMS Found:m/z 230.1312 Calcd for $C_{15}H_{18}O_2$:M, 230.1305. (The IR and HRMS specrtra were obtained on the product mixture of (E)- and (Z)-isomers).

(E)-4-Acetoxy-5-phenyl-1,4-heptadiene ((E)-5b). ^{1}H NMR (400 MHz) δ=0.86 (3H, t, J=7.6Hz, $C\underline{H}_3CH_2$), 2.19 (3H, s, $OCOC\underline{H}_3$), 2.30 (2H, q, J=7.6Hz, $CH_3C\underline{H}_2$), 2.88 (2H, d, J=6.6Hz, $C\underline{H}_2CH$=CH_2), 4.94-5.05 (2H, m, CH=$C\underline{H}_2$), 5.65-5.82 (1H, m, $C\underline{H}$=CH_2), 7.18-7.38 (5H, m, Ph).

(Z)-4-Acetoxy-7-phenyl-5,6,6-trimethyl-1,4-heptadiene ((Z)-5d). ^{1}H NMR (400 MHz) δ=1.14 (6H, s, $PhCH_2C(C\underline{H}_3)_2$), 1.45 (3H, s, $C\underline{H}_3C$=C), 2.10 (3H, s, $OCOC\underline{H}_3$), 2.73 (2H, s, $PhC\underline{H}_2$), 3.07 (2H, d, J=6.4Hz, $C\underline{H}_2CH$=CH_2), 5.03-5.09 (2H, m, CH=$C\underline{H}_2$), 5.74-5.84 (1H, m, $C\underline{H}$=CH_2), 7.12-7.28 (5H, m, Ph). No signal other than these was observed in the ^{1}H NMR spectrum and NOE was observed between 5-methyl (δ=1.45) and 3-methylene (δ=3.07) signals in 2D ^{1}H NOESY spectrum. IR (neat) 1750 cm^{-1} (ester C=O). HRMS Found:m/z 272.1744 Calcd for $C_{18}H_{24}O_2$:M, 272.1774.

(Z)-4-Acetoxy-5,6,6-trimethyl-1,4-heptadiene ((Z)-5e). ^{1}H NMR (400 MHz) δ=1.11 (9H, s, $(C\underline{H}_3)_3CC$=), 1.65 (3H, s, $C\underline{H}_3C$=C), 2.13 (3H, s, $OCOC\underline{H}_3$), 3.02 (2H, d, J=6.1Hz, $C\underline{H}_2CH$=CH_2), 5.01-5.08 (2H, m, CH=$C\underline{H}_2$), 5.72-5.82 (1H, m, $C\underline{H}$=CH_2). No signal other than these was observed in the

^{1}H NMR spectrum and NOE was observed between 5-methyl (δ=1.65) and 3-methylene (δ=3.02) signals in 2D ^{1}H NOESY spectrum. IR (neat) 1731 cm^{-1} (ester C=O). HRMS Found:m/z 196.1462 Calcd for $C_{12}H_{20}O_2$:M, 196.1462.

(Z)-4-Acetoxy-5,6,6-trimethyl-1,4-decadiene ((Z)-5f). ^{1}H NMR (400 MHz) δ=0.87-1.45 (15 H, m, $CH_3CH_2CH_2CH_2C(CH_3)_2$), 1.61 (3H, s, $(CH_3)C$=C), 2.09 (3H, s, $OCOCH_3$), 3.03 (2H, d, J=6.1Hz, CH_2CH=CH_2), 5.01-5.13 (2H, m, CH=CH_2), 5.72-5.82 (1H, m, CH=CH_2). No signal other than these was observed in the ^{1}H NMR spectrum and NOE was observed between 5-methyl (δ=1.61) and 3-methylene (δ=3.03) signals in 2D ^{1}H NOESY spectrum. HRMS Found:m/z 239.1958 Calcd for $C_{15}H_{27}O_2$:M+H, 239.2009.

(E)-4-Acetoxy-5-(4'-chlorophenyl)-6-methyl-1,4-heptadiene ((E)-5g). ^{1}H NMR (400 MHz) δ=0.88 (6H, d, J=7.1Hz, $CH(CH_3)_2$), 2.19 (3H, s, $OCOCH_3$), 2.69 (2H, d, J=6.6Hz, CH_2CH=CH_2), 2.92 (1H, m, J=7.1Hz, $CH(CH_3)_2$), 4.90-5.00 (2H, m, CH=CH_2), 5.58-5.66 (1H, m, CH=CH_2), 7.06 (2H, d, J=8.6Hz, 2'H), 7.31 (2H, d, J=8.6Hz, 3'H). IR (neat) 1756 cm^{-1} (ester C=O). HRMS Found:m/z 278.1107 Calcd for $C_{16}H_{19}ClO_2$:M, 278.1073. (The IR and HRMS spectra were obtained on the product mixture of (E)- and (Z)-isomers).

(Z)-4-Acetoxy-5-(4'-chlorophenyl)-6-methyl-1,4-heptadiene ((Z)-5g). ^{1}H NMR (400 MHz) δ=0.96 (3H, d, J=7.1Hz, $CH(CH_3)_2$), 1.70 (3H, s, $OCOCH_3$), 3.08-3.22 (3H, m, $CH(CH_3)_2$, CH_2CH=CH_2), 5.04-5.24 (2H, m, CH=CH_2), 5.76-5.96 (1H, m, CH=CH_2), 7.31 (2H, d, J=4.4Hz, 2'H), 7.31 (2H, d, J=4.4Hz, 3'H).

(E)-4-Acetoxy-5-benzyl-1,4-heptadiene ((E)-5h). ^{1}H NMR (400 MHz) δ=0.89 (3H, t, J=7.6Hz, CH_3CH_2), 1.91 (2H, q, J=7.6Hz, CH_3CH_2), 2.15 (3H, s, $OCOCH_3$), 3.12 (2H, d, J=6.3Hz, CH_2CH=CH_2), 3.45 (2H, s, $PhCH_2$), 5.04-5.16 (2H, m, CH=CH_2), 5.74-5.82 (1H, m, CH=CH_2), 7.11-7.32 (5H, m, Ph). NOE was observed between benzyl methylene (δ=3.45) and 3-methylene (δ=3.12) signals in 2D ^{1}H NOESY spectrum. IR (neat) 1752 cm^{-1} (ester C=O). HRMS Found:m/z 244.1469 Calcd for $C_{16}H_{20}O_2$:M, 244.1435. (The IR and HRMS spectra were obtained on the product mixture of (E)- and (Z)-isomers).

(Z)-4-Acetoxy-5-benzyl-1,4-heptadiene ((Z)-5h). ^{1}H NMR (400 MHz) δ=0.95 (3H, t, J=7.6Hz, CH_3CH_2), 1.99 (2H, q, J=7.6Hz, CH_3CH_2), 2.10 (3H, s, $OCOCH_3$), 3.12(2H, d, J=6.3Hz, CH_2CH=CH_2), 3.34 (2H, s, $PhCH_2$), 5.04-5.16 (2H, m, CH=CH_2), 5.74-5.82 (1H, m, CH=CH_2), 7.11-7.32 (5H, m, Ph).

(E)-4-Acetoxy-5-benzyl-1,4-heptadiene ((E)-5i). ^{1}H NMR (400 MHz) δ=0.88 (6H, d, J=6.8Hz, $CH(CH_3)_2$), 2.17 (3H, s, $OCOCH_3$), 2.76 (1H, m, J=6.8Hz, $CH(CH_3)_2$), 3.00 (2H, d, J=6.6Hz, CH_2CH=CH_2), 3.44 (2H, s, $PhCH_2$), 4.98-5.07 (2H, m, CH=CH_2), 5.67-5.80 (1H, m, CH=CH_2), 7.19-7.30 (5H, m, Ph). NOE was observed between benzyl methylene (δ=3.44) and 3-methylene (δ=3.00) signals in 2D ^{1}H NOESY spectrum. IR (neat) 1752 cm^{-1} (ester C=O). HRMS Found:m/z 258.1595 Calcd for $C_{17}H_{22}O_2$:M, 258.1618. (The IR and HRMS spectra were obtained on the product mixture of (E)- and (Z)-isomers).

(Z)-4-Acetoxy-5-benzyl-1,4-heptadiene ((Z)-5i). ^{1}H NMR (400 MHz) δ=0.95 (6H, d, J=7.1Hz, $CH(CH_3)_2$), 1.93 (3H, s, $OCOCH_3$), 3.01 (1H, m, $CH(CH_3)_2$), 3.16 (2H, d, J=7.1Hz, CH_2CH=CH_2), 3.44 (2H, s, $PhCH_2$), 5.00-5.16 (2H, m, CH=CH_2), 5.72-5.86 (1H, m, CH=CH_2), 7.19-7.30 (5H, m, Ph).

(Z)-4-Acetoxy-4-(1',2',3',4'-tetrahydro-1'-naphthylidene)-1-butene ((Z)-5j). ^{1}H NMR (400 MHz)

δ=1.83 (2H, quintet, J=6.6Hz, 3'H), 2.06 (3H, s, OCOC$\underline{H}_3$), 2.48 (2H, t, J=6.6Hz, 2'H), 2.70 (2H, t, J=6.6Hz, 4'H), 3.19 (2H, d, J=6.4Hz, C$\underline{H}_2$CH=CH$_2$), 5.06-5.20 (2H, m, CH=C$\underline{H}_2$), 5.75-5.95 (1H, m, C$\underline{H}$=CH2), 7.08-7.23 (3H, m, C$_6\underline{H}_4$), 7.51-7.53 (1H, m, C$_6\underline{H}_4$). NOE was observed between 2'-methylene (δ=2.48) and 3-methylene (δ=3.19) signals in 2D ^{1}H NOESY spectrum. IR (neat) 1751 cm^{-1} (ester C=O). HRMS Found:m/z 242.1307 Calcd for $C_{16}H_{18}O_2$:M, 242.1306.

(E)-4-Acetoxy-5-(2',6'-dichlorophenyl)-1,4-hexadiene ((E)-5k). ^{1}H NMR (400 MHz) δ=1.82 (3H, s, C$\underline{H}_3$C=C), 2.20 (3H, s, OCOC$\underline{H}_3$), 2.77 (2H, d, J=7.1Hz, C$\underline{H}_2$CH=CH$_2$), 4.92-5.29 (2H, m, CH=C$\underline{H}_2$), 5.67-5.77 (1H, m, C$\underline{H}$=CH$_2$), 7.10-7.34 (5H, m, Ph). IR (neat) 1758 cm^{-1} (ester C=O). HRMS Found:m/z 284.0374 Calcd for $C_{14}H_{14}Cl_2O_2$:M, 284.0370. (The IR and HRMS spectra were obtained on the product mixture of (E)- and (Z)-isomers).

(Z)-4-Acetoxy-5-(2',6'-dichlorophenyl)-1,4-hexadiene ((Z)-5k). ^{1}H NMR (400 MHz) δ=1.79 (3H, s, OCOC$\underline{H}_3$), 1.97 (3H, s, C$\underline{H}_3$C=C), 3.28 (2H, d, J=6.8Hz, C$\underline{H}_2$CH=CH$_2$), 5.13 (1H, dq, J=9.8Hz, 1.0Hz, CH=C$\underline{H}_2$), 5.25 (1H, dq, J=18Hz, 2.0Hz, CH=C$\underline{H}_2$), 5.78-5.90 (1H, m, C$\underline{H}$=CH$_2$), 7.10-7.34 (5H, m, Ph).

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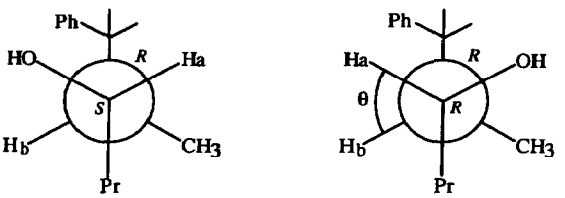
12. For example, in the case of 2,3-dimethyl-2-phenyl-4-heptanol, the signals of the protons at C-3 (Hb) and at C-4 (Ha) were observed as bm and bt, and dq (J=5.1 and 7.1 Hz) and q (J=7.1 Hz), respectively. Thus the diastereomers is considered to have the following configuration and to exist in the conformation of (A) (J_{HaHb}=5.1Hz) and of (B) (J_{HaHb}=0Hz) in which the dihedral angle (θ) may be near to 90°. The diastereomer (A) was converted more readily to (R)- and (S)-MTPA esters compared to diastereomer (B). The signals of 1,2 and 3-methyl and 3-methine protons were observed in the higher field but those of 7-methyl protons were observed in the lower field in the ^{1}H NMR spectrum of the (S)-MTPA ester compared to that of (R)-MTPA ester. Consequently, the configuration is determined to be S at C-4 and thus R at C-3. The configuration of (-)-**3f** was determined to be R in the same way.



A B

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25. The measurement of CD spectrum was done on **3f** because it was difficult to separate the hydrogenated product from solvent. However, the sign of Cotton effect of a hydrogenated sample was the same as that of its non-hydrogenated sample in all other cases in Table 2.
26. The configuration of **3i** was expected to be S according to the assignment by the ^{1}H NMR analysis and its specific rotation although the sign of the Cotton effect of the CD spectrum of the hydrogenated sample was opposite compared to those of of **3g** and **3h** to which was assigned (S)-configuration. This disagreement in the CD spectrum is considered to be due to larger chiroptic contribution of the isopropyl group compared to the benzyl group to the CD spectrum, while substituents R^1 which have higher sequential priority exhibit larger chiroptic contribution than R^2 in all cases other than Entry 9 in Table 2.

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