Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tetrahedron: Asymmetry
Tetrahedron: *Asymmetry* 15 (2004) 3869–3878

Diastereoselective allylation of *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam and (1*R*)-8-phenylmenthyl glyoxylate: synthesis of (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide

Katarzyna Kiegiel,[a] Tomasz Bałakier,[a] Piotr Kwiatkowski[b] and Janusz Jurczak[a,b,*]

[a]*Department of Chemistry, Warsaw University, 02-093 Warsaw, Poland*
[b]*Institute of Organic Chemistry, Polish Academy of Sciences, 01-224 Warsaw, Poland*

Received 1 September 2004; accepted 25 October 2004

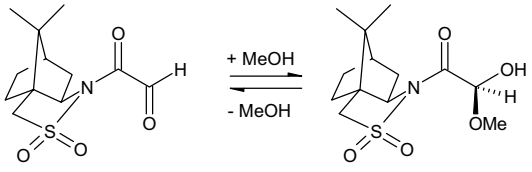
Abstract—The diastereoselective addition of allylsilanes and allylstannanes to *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam **1** and (1*R*)-8-phenylmenthyl glyoxylate **7** in the presence of Lewis acids has been studied. We obtained diastereoselectivities up to 84% and 94% for the allylation of **2** and **7**, respectively. The application of the allylation products of **1** or **2** in the synthesis of 4-butanolides, for example (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide **13** is presented.

1. Introduction

Chiral α-hydroxy-γ,δ-unsaturated esters or amides are important building blocks in organic synthesis and many various synthetic intermediates can be readily prepared from these compounds.[1,2] The efficient methods for synthesis of α-hydroxy-γ,δ-unsaturated derivatives of carboxylic acids are the ene reaction,[3] the glycolate enolate allylation,[4] and the nucleophilic addition of allylic reagents to chiral glyoxylates[5] or to chiral glyoxymides.[6] There are also other known stereoselective methods for such allylations including an enantioselective catalytic approach[7] or applying chiral allylating reagents[8] to alkyl glyoxylates. One of the potential applications of this methodology seems to be the diastereoselective synthesis of chiral 2,4-disubstituted-4-butanolides.

Chiral 4-butanolides form an important and interesting group of biologically active compounds, which could also be applied as synthetically useful chiral building blocks.[9] Among them, 2-hydroxy-4-hydroxymethyl-4-butanolides attracted our attention as synthetic targets. It has been found that (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide is responsible for the elicitation of food intake in mammals.[10] Its (2*R*,4*R*)-enantiomer has been used as a starting material in the synthesis of the A-ring of a vitamin D analog.[11] 2-Hydroxy-4-hydroxymethyl-4-butanolides are synthesized usually via degradation of appropriate sugars[12] or using enzymatic procedures[13] and others.[14]

Herein, we report the extended studies on the diastereoselective synthesis of 2-hydroxypent-4-enoic acid derivatives using the asymmetric addition of allylic reagents to *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam **1** or its hemiacetal **2**[15] (Scheme 1), followed by the preparation of (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide. For comparison we also studied allylation reaction of 8-phenylmenthyl glyoxylate.[16]



(2*R*)- **1** (2*R*)- **2**

Scheme 1.

* Corresponding author. Tel.: +48 22 6320578; fax: +48 22 6326681; e-mail: jurczak@icho.edu.pl

0957-4166/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2004.10.025

2. Results and discussion

2.1. Preliminary investigations of the allylation of *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam 1

In the first stage of our studies, we resolved to apply the allylic Grignard reagent (Scheme 2, Table 1, entry 1). The mixture of diastereomers (2′*S*)-**3** and (2′*R*)-**3** (70% de) was obtained only in 35% yield (46% of bornane-10,2-sultam was recovered). When the Grignard addition was modified using tetraisopropoxytitanium (entries 2 and 3), the reaction yield increased substantially, but the diastereoselectivity dropped.

Application of allyl bromide in the presence of zinc dust (entries 4–6) improved the reaction yield, but the stereoselectivity remained on the level of 40% de.

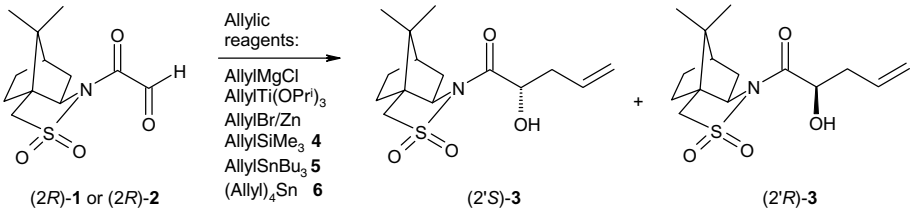
The above-presented data show that the addition of the Grignard reagent to the formyl group is accompanied by another process, namely the reaction of the allylic reagent with the imido group of **1**. This results in the formation of bornane-10,2-sultam; the labile nature of the imide bond in compound **1** precludes the use of such organometallic reagents for allylation reactions.

2.2. Allylation of compounds 1 and 2 with allyltrimethylsilane or allyltributylstannane

N-Glyoxyloyl-(2*R*)-bornane-10,2-sultam **1** and its hemiacetal **2** were reacted with allyltrimethylsilane **4** or with allyltributylstannane **5** (and in one case with tetraallyltin **6**) in the presence of various Lewis acids. Under such conditions, we did not observe splitting of the bornane-10,2-sultam. Results of our experiments are shown in Table 2. Addition of **4** or **5** carried out in the presence of a strong and chelating Lewis acid (entries 1–5) afforded the mixture of diastereomers (2′*S*)-**3** and (2′*R*)-**3** (Scheme 2) in moderate to good yields but the asymmetric induction was low (26–40% de). The use of nonchelating Lewis acids, for example, $BF_3{\cdot}Et_2O$ (entries 6–11) improved the diastereoselectivity substantially (up to 60% de). A similar result concerning the diastereoselectivity was obtained for the less active catalyst $MgBr_2{\cdot}2Et_2O$ (entry 12). The best results in terms of both chemical and diastereomeric excesses (58–84% de) were obtained when the reaction was performed in the presence of $ZnCl_2$ or $ZnBr_2$ (entries 13–19); the latter Lewis acid was more selective. Application of hemiacetal **2** instead of free aldehyde **1** in the investigated reaction often improved the yield, but had virtually no influence on the diastereoselectivity of the process (compare entries 13 and 14, or 15 and 16). When comparing the allylating reagents in the reaction catalyzed by $ZnBr_2$, allyltrimethylsilane **4** gives a higher diastereoselectivity (up to 84% de), while the reaction with tin reagents **5** and **6** (58–76% de, entries 17–19) is faster, less demanding and more repeatable. The advantage of the presented synthesis is its potential for easy preparation of the pure diastereomer (2′*S*)-**3** by a simple, single crystallization.

2.3. Allylation of (1*R*)-8-phenylmenthyl glyoxylate with allyltrimethylsilane or allyltributylstannane

The very promising results obtained using *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam **1** or hemiacetal **2** should be, however, confronted with an analogous reaction using (1*R*)-8-phenylmenthyl glyoxylate **7**. There are few examples of allylation of this substrate,[5] with the resulting diastereomeric excesses not exceeding 72%. The glyoxylate **7** was also used for the ene reaction with propene in the presence of $SnCl_4$, which afforded (2′*S*)-**8** in very high yields and diastereoselectivities.[3]



Scheme 2.

Table 1. Results of the reaction of **1** with various allylating reagents[a]

Entry	Allylating reagent	Additive	Time (h)	Yield[b] (%)	Diastereomeric ratio (2′*S*)-**3**:(2′*R*)-**3**[c]	De (%)	Auxiliary recovered (%)
1	AllylMgCl	—	23	35	85:15	70	46
2	AllylMgCl	Ti(OPr^i)$_4$	3	63	70:30	40	8
3	AllylTi(OPr^i)$_3$	—	4	45	60:40	20	40
4	AllylBr	Zn	1	40	70:30	40	14
5	AllylBr	Zn, sonication	1	55	70:30	40	10
6	AllylBr	Zn, 10% $TiCl_4$	1	80	70:30	40	7

[a] All reactions were carried out in THF at −78 °C.
[b] Isolated yield.
[c] Diastereoisomeric ratio was determined by ^{1}H NMR.

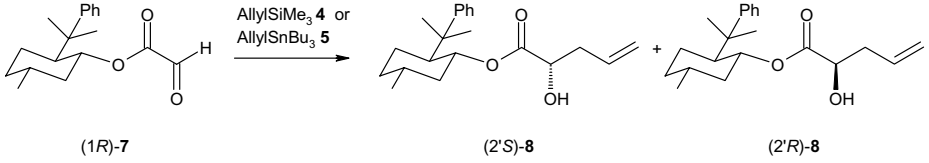
Table 2. Results of the reaction of **1** or **2** with allyltrimethylsilane **4**, allyltributylstannane **5**, or tetraallyltin **6**, carried out in the presence of various Lewis acids[a]

Entry	Substrate	Allylating reagent	Lewis acid (1 equiv)	Temp (°C)	Time (h)	Yield[b] (%)	Diastereomeric ratio (2′*S*)-**3**:(2′*R*)-**3**[c]	De (%)
1	**1**	**4**	$SnCl_4$	−40	4	80	63:27	26
2	**1**	**4**	$SnCl_4$	−78	18	45	69:31	38
3	**2**	**5**	$SnCl_4$	−20	2	95	70:30	40
4	**1**	**4**	$TiCl_4$	−78	65	55	65:35	30
5	**2**	**5**	$TiCl_4$	−20	2	86	65:35	30
6	**1**	**4**	$BF_3{\cdot}Et_2O$	20	1	70	75:25	50
7	**1**	**4**	$BF_3{\cdot}Et_2O$	0	1	65	74:26	48
8	**1**	**4**	$BF_3{\cdot}Et_2O$	−20	1	65	80:20	60
9	**1**	**4**	$BF_3{\cdot}Et_2O$	−40	4	62	79:21	58
10	**1**	**4**	$BF_3{\cdot}Et_2O$	−78	18	45	72:28	44
11	**2**	**5**	$BF_3{\cdot}Et_2O$	20	1	47	80:20	60
12	**1**	**4**	$MgBr_2{\cdot}2Et_2O$	25	21	70	80:20	60
13	**1**	**4**	$ZnCl_2$	0	2	70	89:11	78
14	**2**	**4**	$ZnCl_2$	0	3	85	86:14	72
15	**1**	**4**	$ZnBr_2$	0	2	75	91:9	82
16	**2**	**4**	$ZnBr_2$	0	6	95	92:8	84
17	**2**	**5**	$ZnBr_2$	20	2	91	82:18	64
18	**2**	**5**	$ZnBr_2$	0	3	65	88:12	76
19	**2**	**6**	$ZnBr_2$	0	2	97	79:21	58

[a] All reactions were carried out in the presence of 1 equiv of Lewis acids in CH_2Cl_2.
[b] Isolated yield.
[c] Diastereomeric ratio was determined by ^1H NMR, and in some cases the reaction mixture transformed to 4-allyl-2,2-dimethyl-1,3-dioxolane with de confirmed using gas chromatography (GC) on a chiral capillary column.

We employed 8-phenylmenthyl glyoxylate **7** for the allylation reaction using the silyl reagent **4** as well as the tin reagent **5** in the presence of various Lewis acids (Scheme 3, Table 3).

Regardless the type of allylating reagent and catalyst used, we obtained very good yields (77–99%) and diastereoselectivities (86–94%). The best results were obtained using allyltributyltin and either $BF_3{\cdot}Et_2O$ or $SnCl_4$ as Lewis acids (99% yield, 92% de, entries 2 and 6). $ZnBr_2$ also provides a very good diastereoselectivity (94% de, entry 4) but the yields slightly lower. Compared to the reaction using *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam **1**, this approach gives much higher



Scheme 3.

Table 3. Results of the reaction of **7** with **4** or **5**, carried out in the presence of various Lewis acids[a]

Entry	Allylating reagent	Lewis acid	Temp (°C)	Yield[b] (%)	Diastereomeric ratio (2′*S*)-**3**:(2′*R*)-**3**[c]	De (%)
1	**4**	$BF_3{\cdot}Et_2O$	20	95	93:7	86
2	**5**	$BF_3{\cdot}Et_2O$	20	99	96:4	92
3	**4**	$ZnBr_2$	20	84	94:6	88
4	**5**	$ZnBr_2$	20	77	97:3	94
5	**4**	$SnCl_4$	−20	93	94:6	88
6	**5**	$SnCl_4$	−20	99	96:4	92
7	**4**	$TiCl_4$	−20	91	95:5	90
8	**5**	$TiCl_4$	−20	99	93:7	86

[a] All reactions were carried out in the presence of 1 equiv of Lewis acids in CH_2Cl_2 for 1 h.
[b] Isolated yield.
[c] The mixture of **8** was transformed to 4-allyl-2,2-dimethyl-1,3-dioxolane and the ratio determined using gas chromatography (GC) on a chiral capillary column.

diastereoselectivities, but, in contrary to that reaction, it is difficult to purify the product to obtain a single diastereomer.

2.4. The determination of the extent and direction of the asymmetric induction

Following work-up, the crude reaction mixtures were analyzed by ^{1}H NMR to establish the diastereomeric ratio of the adducts (2′*S*)-**3** and (2′*R*)-**3**. The diastereomeric excess was confirmed by separation of the mixture into single diastereomers via flash chromatography or by analysis of the isopropylidene derivative of pent-4-ene-1,2-diol (4-allyl-2,2-dimethyl-1,3-dioxolane) using gas chromatography (GC) on a chiral capillary column. The compound suitable for GC analysis was obtained by reduction of **3** or **8** to pent-4-ene-1,2-diol, followed by isopropylidene protection of the hydroxy groups. The major diastereomer (2′*S*)-**3** was crystallized to afford the single crystals suitable for X-ray analysis. The structure of (2′*S*)-**3** showing the relative configuration of the stereogenic centers is presented in Figure 1.

The data presented in Tables 1 and 2 show that all addition reactions lead to the (2′*S*)-**3** diastereomer, preferentially. Rationalization of our results concerning allylation of **1** and **2** is based on the earlier work of Oppolzer et al.[17] and Curran et al.,[18] and later by us[15a,19] formulated for the noncatalyzed reactions.

As suggested by X-ray analysis of *N*-acryloyl- and *N*-crotonoyl-(2*R*)-bornane-10,2-sultam,[17,18] for *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam[15b] **1** the more stable CO/CHO *s-cis* planar conformer **B** should be preferred over the conformer *s-trans* **A** due to electrostatic and/or dipole–dipole repulsion between the sultam oxygen and glyoxyloyl moiety (Scheme 4). It is also noteworthy that in the presence of a chelating Lewis acid, such as $SnCl_4$, $TiCl_4$, $ZnBr_2$, $MgBr_2{\cdot}2Et_2O$, the CO/CHO *s-cis* conformation of the chiral glyoxymides and glyoxylates is favored. Therefore, the

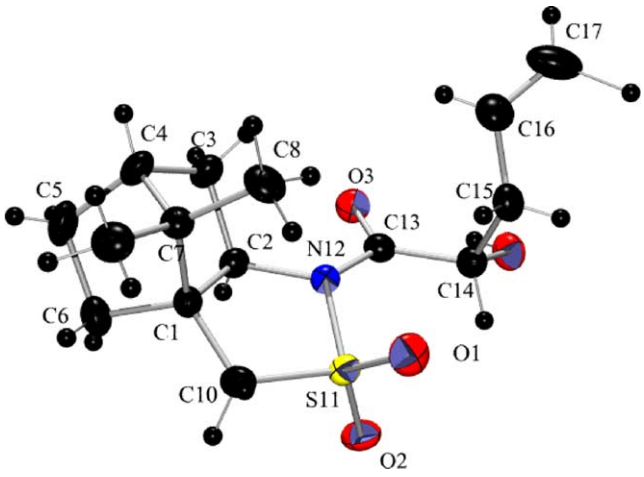


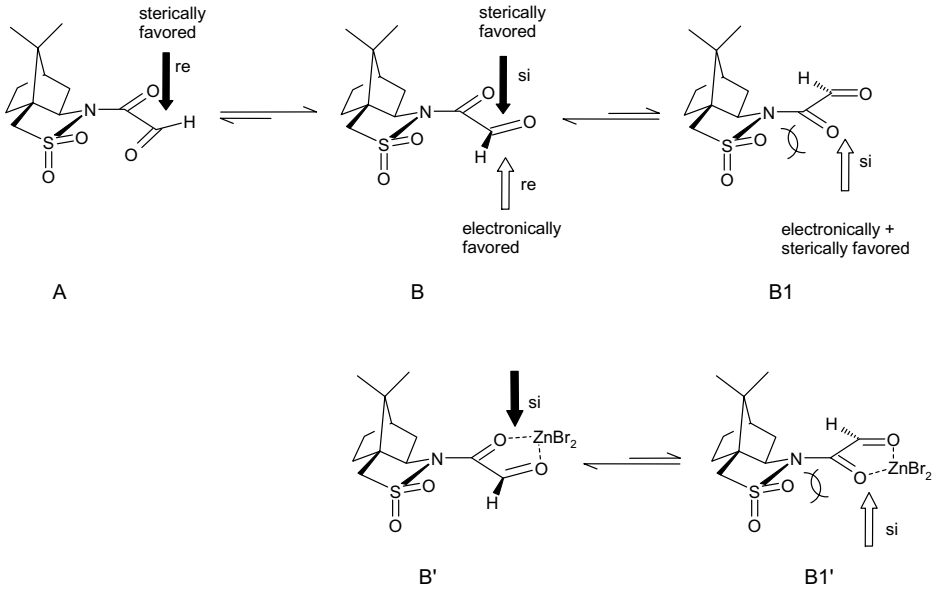
Figure 1. ORTEP drawing of compound (2′*S*)-**3**.

approach of the allylic reagent to conformer **B** should occur from the topside of the bornane skeleton. There is another possibility; the approach of the allylic reagent from the bottom side to the less stable but most reactive (in terms of LUMO level and atomic coefficients) SO_2/CO *syn*-periplanar, CO/CHO *s-cis* conformer **B1**. In this case sterically controlled approach is reinforced by the cooperative stereoelectronic effect.[19] The same reasoning seems to be correct in the case of reactions catalyzed by Lewis acids (conformers **B**′ and **B1**′).

In the case of the allylation of (1*R*)-8-phenylmenthyl glyoxylate we observed the same direction of asymmetric induction to (2′*S*)-**8**.[5a]

2.5. The synthesis of chiral 4-butanolides by iodolactonisation of 3

One of the useful methods for the synthesis of heterocyclic intermediates like 4-butanolides[1c,20] or tetra-



Scheme 4. Stereochemical model of allylation.

hydrofurans[21] is the iodolactonization reaction of homoallylic alcohols. We found in the literature that the halolactonization reaction is mediated by a chiral auxiliary.[24] We studied the iodolactonization process of enantiomerically pure homoallyl alcohol **3**. This reaction afforded a 75:25 mixture of 2,4-disubstituted-4-butanolides (2*S*,4*R*)-**9** and (2*S*,4*S*)-**9** (Scheme 5).

The chemical yield depends on the reaction conditions, and can be improved upon substantially when the reaction is carried out in the mixture of the tetrahydrofuran and phosphate buffer (pH = 7.4). Chromatographic separation of the crude reaction mixture afforded both diastereomeric adducts in analytically pure form. These adducts were separately reduced to give the products (2*S*,4*S*)-**10** and (2*S*,4*R*)-**10** without racemization.[23] For final justification of the configuration of our products, we decided to transform the compound (2*S*,4*S*)-**10** into its crystalline derivative (2*S*,4*S*)-**11** (Scheme 5), which was then subjected to X-ray analysis. The results of this study fully confirmed the configurations proposed by us and are presented in Figure 2.

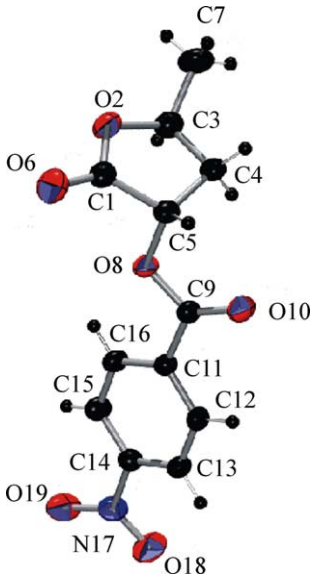
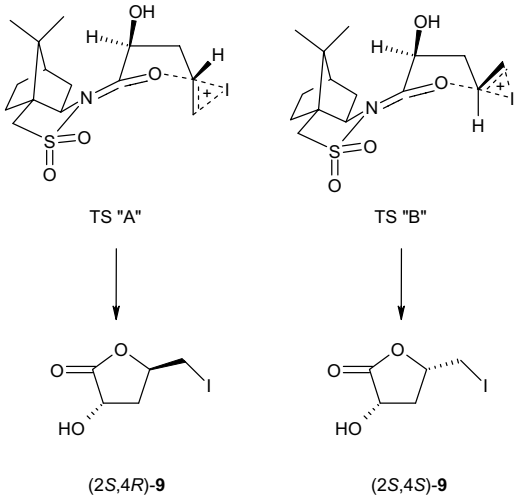


Figure 2. ORTEP drawing of compound (2*S*,4*S*)-**11**.

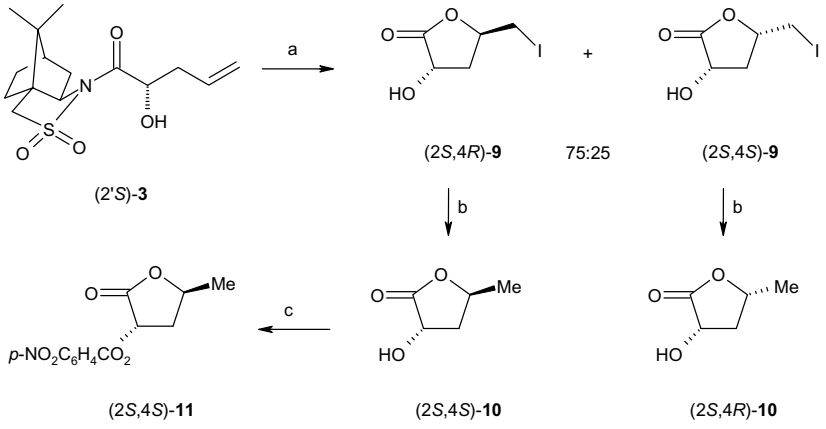
The *trans*-isomer (2*S*,4*R*)-**9** was preferred in iodolactonization reaction. Contrary to the imide (2′*S*)-**3**, bromo- and iodolactonization of 2-hydroxypent-4-enoic acid proceeds in favor of the *cis*-isomer.[20,1c] For rationalization of our result we proposed the transition states **A** and **B**, which are presented in Scheme 6. The interaction between the chiral auxiliary [(2*R*)-bornane-10,2-sultam] and the C_α-stereogenic center forces the C_α-hydroxyl substituent to adapt a pseudoaxial orientation in both competing transition states **A** and **B**. We assume that transition state **A** providing the *trans*-isomer (2*S*,4*R*)-**9** is favored over **B**, because of the lack of 1,3-diaxial-like interactions between the C_α-hydroxyl substituent and 'iodine ion' (olephinic moiety).



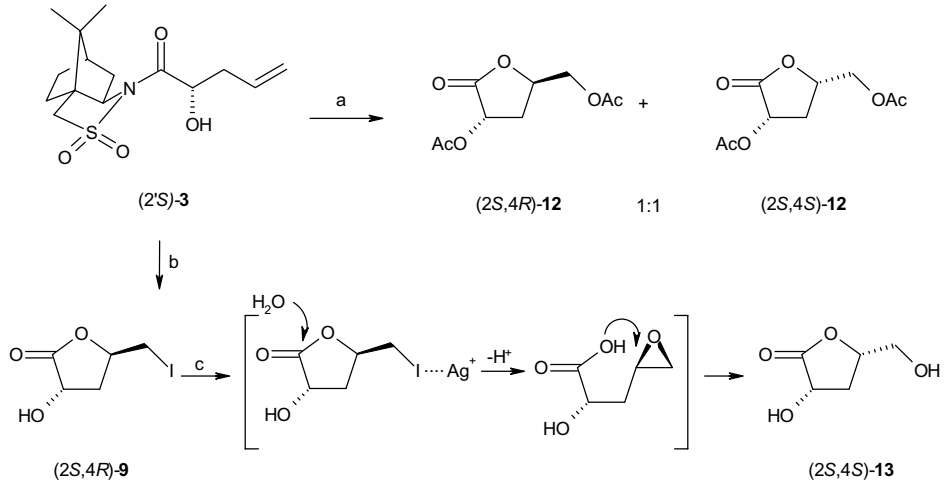
Scheme 6. Stereochemical model of iodolactonization.

2.6. Synthesis of (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide 13

First we tried to construct the diacetyl derivatives of (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide by acetoxylactonization of (2′*S*)-**3** (Scheme 7). This attempt



Scheme 5. Reagents and conditions: (a) 3 equiv I_2, THF/H_2O 1.5:1, pH = 7.4, 24 h; (b) Bu_3SnH, AIBN, toluene, 100 °C; (c) *p*-$NO_2C_6H_4COCl$, pyridine/CH_2Cl_2.



Scheme 7. Reagents and conditions: (a) $(NH_4)_2S_2O_8$, CF_3SO_3H, AcOH, 70 °C; (b) 3 equiv I_2, THF/H_2O 1.5:1, pH = 7.4, 24 h; (c) $AgNO_2$, EtOH/H_2O 1:1, reflux, 3 h.

was unsuccessful, because this reaction afforded a 1:1 mixture of *cis*- and *trans*-isomers, (2*S*,4*R*)-**12** and (2*S*,4*S*)-**12**, respectively, as resulted from the ^{1}H NMR study.[12b,c] Therefore, we obtained the desired compound (2*S*,4*S*)-**13**[10,12–14] by treating the major product of iodolactonization (2*S*,4*R*)-**9** with the silver nitrite in aqueous ethanol (Scheme 7).[24]

One can see that the latter reaction proceeds with inversion of configuration at the C-4 stereogenic center. The stereochemical outcome can be explained as outlined in Scheme 7. We speculate that the inversion of the C-4 stereocenter is established through the epoxide intermediate giving rise to (2*S*,4*S*)-**13** by 5-*exo* ring closure, as is generally observed. The product of the 6-*endo* ring closure was not observed in the post-reaction mixture.

3. Conclusions

Herein, we have reported the results of the stereoselective two-step conversion of *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam **1** into enantiomerically pure γ-butyrolactones. The auxiliary mediates diastereoselective C–C bond formation in the first step, and the diastereoselective heterocyclization in the second step. The results presented above demonstrate that it is possible to control the diastereoselectivity of the allylation of glyoxylic acid derivatives, and then to control the diastereoselectivity of iodolactonization. Additionally, we have presented a highly efficient and diastereoselective method of allylation of 8-phenylmenthyl glyoxylate.

4. Experimental

4.1. General

Solvents were freshly distilled from CaH_2 or Na/benzophenone. Analytical TLC was performed using plates precoated with silica gel 60 F_{254} (Merck); detection by spraying with a solution of 2% molybdic acid and 1% $Ce(SO_4)_2$ in 15% H_2SO_4. Flash chromatography was performed using silica gel 60 (40–63 μm) (Merck). Melting points (uncorrected) were determined using a Köfler-type hot-stage apparatus (Boetius). Optical rotations were taken using Perkin–Elmer-241 polarimeter. IR spectra in KBr pellets were recorded on a Perkin–Elmer 1640 FTIR spectrometer. ^{1}H and ^{13}C NMR spectra were recorded using Varian Gemini-200 or Varian-Unity Plus-500 spectrometers. Mass spectra were recorded using AMD-604 Intectra instrument in the electron impact (EI) mode. Ratio of (*R*)/(*S*)-4-allyl-2,2-dimethyl-1,3-dioxolane was determined by gas chromatography performed using a Shimadzu GC unit equipped with a capillary chiral column β-dex 120 (permethyl-β-cyclodextrin, 30 m × 0.25 mm I.D. Supelco, Bellefonte, USA). Chromatography conditions: carrier gas—nitrogen, 100 kPa; injection temp 200 °C; detector temp 250 °C; oven temp 90 °C, (*R*)-isomer, 7.1 min, (*S*)-isomer, 7.3 min.

4.2. Synthesis of the adducts (2′*S*)-3 and (2′*R*)-3

4.2.1. Addition of allylmagnesium chloride to *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam 1. To a stirred solution of *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam **1** (272 mg, 1 mmol) in dry THF (ca. 10 mL) under argon, the solution of allylmagnesium chloride in THF (2 M, 0.75 mL, 1.5 mmol) was added dropwise at −78 °C, and stirring continued at this temperature for 23 h. The reaction was quenched with satd NH_4Cl and the aqueous layer extracted with Et_2O (3 × 30 mL). The separated organic layers were combined, dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate, 9:1 → 7:3) of the residue afforded the homoallyl alcohols **3** (107 mg, 35%).

4.2.2. Addition of allyltitanium reagents to *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam 1. To a solution of the allyltitanium reagent (1.5 mmol), prepared according to the procedure given below, the solution of compound **1** (272 mg, 1 mmol) in dry THF (10 mL) was added dropwise at −78 °C. The reaction was stirred at the same

temperature for the period of time indicated in Table 1. The reaction was quenched with satd NH_4Cl and extracted with Et_2O (3×30 mL). The organic layers were combined, dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate) of the residue afforded homoallyl alcohols **3**.

4.2.2.1. Preparation of the allyltitanium reagents

4.2.2.1.1. The complex of allylmagnesium chloride with $Ti(OPr^i)_4$. A solution of allylmagnesium chloride in THF (2 M, 0.75 mL, 1.5 mmol) was added to a cooled (−78 °C) solution of titanium(IV) isopropoxide (0.44 mL, 1.5 mmol) in dry THF (1.5 mL) under an argon atmosphere. The mixture was stirred at the same temperature for 10 min.

4.2.2.1.2. Allyltri(isopropoxy)titanium. The solution of allylmagnesium chloride in THF (2 M, 0.75 mL, 1.5 mmol) was added to a solution of tri(isopropoxy)titanium chloride in dry CH_2Cl_2 (1 M, 1.5 mL, 1.5 mmol), at −78 °C, under an argon atmosphere. The mixture was stirred at −78 °C for 10 min.

4.2.3. Addition of allyl bromide to *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam 1 in the presence of zinc powder. To a mixture of allyl bromide and zinc (prepared according to the procedure given below), a solution of compound **1** (1 mmol) in dry THF (10 mL) was added dropwise at −78 °C. The reaction was stirred at the same temperature for the period of time indicated in Table 1. The reaction was quenched with satd NH_4Cl and extracted with Et_2O (3×30 mL). The organic layers were combined, dried $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate) of the residue afforded homoallyl alcohols **3**.

4.2.3.1. Preparation of the mixture of allyl bromide and zinc

4.2.3.1.1. Method A. Allyl bromide (0.13 mL, 1.5 mmol) was added to the suspension of zinc powder (98 mg, 1.5 mmol) in dry THF (2.5 mL). The mixture was stirred at room temperature for 30 min.

4.2.3.1.2. Method B. A suspension of zinc powder (98 mg, 1.5 mmol) in dry THF (2.5 mL) was sonicated (40 kHz) for 15 min. Then allyl bromide (0.13 mL, 1.5 mmol) was added and the mixture was stirred at room temperature for 30 min.

4.2.3.1.3. Method C. The solution of allyl bromide (0.13 mL, 1.5 mmol) in dry THF (1.5 mL) was added dropwise to a suspension of zinc powder (98 mg, 1.5 mmol) and titanium(IV) chloride (17 μL, 0.15 mmol) in dry THF (1 mL), and stirring continued at room temperature for 15 min.

4.2.4. Addition of allyltrimethylsilane to *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam 1 or its hemiacetal 2. To a stirred solution of **1** or **2** (1 mmol) in dry CH_2Cl_2 (10–15 mL) at a temperature indicated in Table 2, the Lewis acid (1 mmol) was added under argon. After additional stirring (5 min), allyltrimethylsilane (320 μL, 2 mmol) was added dropwise. Stirring was continued for the period of time indicated in Table 2. The reaction was quenched with satd NH_4Cl and extracted with Et_2O (3×30 mL). The organic layers were combined, dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate) afforded homoallyl alcohols **3**.

4.2.5. Addition of allylstannanes to hemiacetal 2. To a stirred solution of **2** (303 mg, 1 mmol) in dry CH_2Cl_2 (5–10 mL) the Lewis acid (1.0–1.1 mmol) was added. After additional stirring (10 min), allyltributyltin **5** (402 μL, 1.3 mmol) or tetraallyltin **6** (84 μL, 0.35 mmol) was added dropwise at a temperature indicated in Table 2. Stirring was continued for the period of time indicated in Table 2. The reaction was quenched with 20% NH_4F and extracted with Et_2O (3×30 mL). The combined organic layers were dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate, 9:1 → 7:3) afforded homoallyl alcohols **3**.

4.2.6. Analytical and spectral data for the compound (2′*S*)-3. Mp 138–139 °C; $[\alpha]_D^{20} = -105.0$ (*c* 2.2, $CHCl_3$); ^{1}H NMR (200 MHz, $CDCl_3$), *δ*: 5.90–5.70 (m, 1H, C*H*=CH_2), 5.20–5.07 (m, 2H, C=C*H*$_2$), 4.89–4.78 (m, 1H, C*H*OH), 3.94 (dd, *J* = 7.4, 5.0 Hz, 1H, C*H*N), 3.52 ($^1/_2$ ABq, *J* = 13.8 Hz, 1H, C*H*SO_2), 3.48 ($^1/_2$ ABq, *J* = 13.8 Hz, 1H, C*H*SO_2), 3.08 (d, *J* = 7.7 Hz, 1H, O*H*), 2.75–2.41 (m, 2H,C*H*$_2$) 2.15–1.29 (m, 7H, $3 \times CH_2$ and $1 \times$C*H*), 1.14 (s, 3H, C*H*$_3$), 0.98 (s, 3H, C*H*$_3$); ^{13}C NMR (50 MHz, $CDCl_3$), *δ*: 174.2, 132.0, 118.9, 70.3, 64.9, 52.9, 48.9, 47.8, 44.5, 39.8, 38.2, 32.7, 26.4, 20.7, 19.8; IR (KBr): 3552, 3001, 2959, 1696, 1641, 1331, 1058, 774; EIMS *m*/*z* (%): 313 (M^+, 1.3), 295 (1.8), 272 (33), 199 (9), 135 (100), 93 (47), 71 (13), 55 (6); Anal. Calcd for $C_{15}H_{23}NO_4S$: C, 57.5; H, 7.4; N, 4.0; S, 10.2; found: C, 57.3; H, 7.5; N, 4.4; S, 10.2.

4.2.7. Analytical and spectral data for the compound (2′*R*)-3. Mp 69–70 °C; $[\alpha]_D^{20} = -97.7$ (*c* 1.08, $CHCl_3$); ^{1}H NMR (200 MHz, $CDCl_3$); *δ*: 5.97–5.76 (m, 1H, C*H*=CH_2), 5.25–5.11 (m, 2H, C=C*H*$_2$), 4.72–4.61 (m, 1H, C*H*OH), 3.91 (dd, *J* = 7.7, 5.1 Hz, 1H, C*H*N), 3.53 ($^1/_2$ ABq, *J* = 14.0 Hz, 1H, CH_2SO_2), 3.48 ($^1/_2$ ABq, *J* = 14.0 Hz, 1H, CH_2SO_2), 3.14 (d, *J* = 7.4 Hz, 1H, O*H*), 2.73–2.40 (m, 2H, C*H*$_2$), 2.29–1.20 (m, 7H, $3 \times CH_2$ and $1 \times$C*H*), 1.15 (s, 3H, C*H*$_3$), 0.97 (s, 3H, C*H*$_3$); ^{13}C NMR (50 MHz, $CDCl_3$): *δ*: 171.8, 133.1, 118.5, 70.3, 65.3, 52.9, 49.3, 47.9, 44.5, 38.1, 37.0, 32.8, 26.5, 20.7, 19.9; IR (KBr): 3561, 3078, 2964, 1699, 1640, 1134, 1056, 764; EIMS *m*/*z* (%): 313 (M^+, 3), 295 (6), 272 (31), 199 (8), 135 (100), 93 (48), 71 (15), 55 (8); HR-EIMS calcd for $C_{15}H_{23}NO_4S$ (M^+): 313.13478, found: 313.1352; calcd for $C_{12}H_{18}NO_4S$ ($M^+ - C_3H_5$): 272.0956, found: 272. 0951.

4.3. Addition of allyltrimethylsilane or allyltributylstannane to (1*R*)-8-phenylmenthyl glyoxylate 6

To a stirred solution of **6** (289 mg, 1 mmol) in dry CH_2Cl_2 (10 mL) the Lewis acid (1.0–1.1 mmol) was added and after 10 min at a temperature indicated in Table 3 allyltrimethylsilane (320 μL, 2 mmol) or allyltributyltin (402 μL, 1.3 mmol) was added. Stirring was continued for the period of time indicated in Table 3. The reaction was quenched with 20% NH_4Cl and extracted with Et_2O (3×30 mL). The combined organic

layers were pooled, dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate) afforded homoallyl alcohols **8**. The NMR data of compounds **8** are in agreement with those described in the literature.[5a] Specific rotations for (2′*S*)-**8**: $[\alpha]_D^{20} = -7.9$ (*c* 1.82, $CHCl_3$); lit.[5a] $[\alpha]_D = -6.2$ (*c* 1.75, $CHCl_3$).

4.4. Synthesis of (2*S*,4*R*)- and (2*S*,4*S*)-2-hydroxy-4-iodomethyl-4-butanolide 9

To a solution of compound (2′*S*)-**3a** (1.0 g, 3.19 mmol) in a mixture of THF/phosphoric buffer (pH = 7.4) (20 mL, 12:8) was added iodine (2.45 g, 9.6 mmol) at ambient temperature. The reaction mixture was stirred for 24 h. To the resultant solution was added satd $Na_2S_2O_3$ (5 mL) and stirring continued for 15 min. Then the layers were separated and the aqueous layer extracted with Et_2O (3×50 mL). The organic layers were combined, washed twice with satd $NaHCO_3$, once with satd brine, dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography (hexane–ethyl acetate 8:2 → 7:3) of the residue afforded the compounds (2*S*,4*R*)-**9** (349 mg, 1.44 mmol, 45%) and (2*S*,4*S*)-**9** (116 mg, 0.48 mmol, 15%). (2*R*)-Bornane-10,2-sultam (615 mg, 2.86 mmol, 89%) was also isolated after the chromatography.

4.4.1. Analytical and spectra data for the compound (2*S*,4*R*)-9. Colorless oil; $[\alpha]_D^{20} = -9.3$ (*c*, 1.22, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$), δ: 4.77–4.71 (m, 1H, C*H*CH_2I), 4.67 (t, *J* = 7.6 Hz, 1H, C*H*OH), 3.37 ($^1/_2$ ABq, *J* = 10.0, 4.4 Hz, 1H, C*H*I), 3.36 ($^1/_2$ ABq, *J* = 10.0, 6.8 Hz, 1H, C*H*I), 2.95 (s, 1H, O*H*), 2.44 (dd, *J* = 7.6, 6.4 Hz, 2H, CH_2CHOH), ^{13}C NMR (125 MHz, $CDCl_3$), δ: 176.8, 76.7, 67.4, 35.7, 7.3; IR (film): 3386, 1778, 1174, 1116, 611; EIMS *m*/*z* (%): 242 (M^+) (7.6), 169 (2.6), 141 (5.0), 127 (7.0), 77 (7.0), 71 (100), 43 (72); HR-EIMS calcd for $C_5H_7IO_3$ (M^+): 241.9440, found: 241.9419.

4.4.2. Analytical and spectral data for compound (2*S*,4*S*)-9. Colorless oil; $[\alpha]_D^{20} = -39.24$ (*c*, 1.26, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$), δ: 4.60 (dd, *J* = 11.0, 8.5 Hz, 1H, C*H*OH), 4.51–4.41 (m, 1H, C*H*CH_2I), 3.46 ($^1/_2$ ABq, *J* = 10.0, 5.0 Hz, 1H, C*H*I), 3.32 ($^1/_2$ ABq, *J* = 10.0, 7.5 Hz, 1H, C*H*I), 3.3 (br s, 1H, O*H*), 2.94–2.86 (m, 1H, *CH*CHOH), 2.05–1.90 (m, 1H, *CH*CHOH); ^{13}C NMR (125 MHz, $CDCl_3$), δ: 176.5, 75.5, 68.8, 37.3, 5.4; IR (film in CCl_4): 3409, 1777, 1171, 1118, 997, 798; EIMS *m*/*z* (%): 242 (M^+) (46), 167 (9), 141 (6), 127 (6), 71 (100), 43 (75); Anal. Calcd for $C_5H_7IO_3$: C, 24.81; H, 2.92; found: C, 24.85; H, 3.10.

4.5. Synthesis of (2*S*,4*S*)-2-hydroxy-4-methyl-4-butanolide 10

To the solution of (2*S*,4*R*)-2-hydroxy-4-iodomethyl-4-butanolide (2*S*,4*R*)-**9** (142 mg, 0.58 mmol) in dry toluene (3 mL) was added a crystal of AIBN, followed by slow addition of tri(*n*-butyl)tin hydride (0.19 mL, 0.70 mmol) under argon. The reaction mixture was heated at 100 °C for 18 h. Then the solvent was evaporated, the residue was cooled (0 °C), and a mixture of trifluoroacetic acid and water (2 mL, 9:1) added. The reaction mixture was stirred at the same temperature for 1 h and then concentrated in vacuo. Flash chromatography of the residue (hexane–ethyl acetate 3:1) afforded the corresponding butanolide (60 mg, 0.52 mmol, 89%) as an oil.

4.5.1. Analytical and spectral data for the compound (2*S*,4*S*)-10. Colorless oil; $[\alpha]_D^{20} = -64.5$ (*c*, 1.9, MeOH); lit.[21a] $[\alpha]_D^{20} = -59.8$ (*c* 1, MeOH); ^{1}H NMR (500 MHz, $CDCl_3$), δ: 4.86–4.78 (m, 1H, C*H*CH_3), 4.58 (t, *J* = 7.5 Hz, 1H,C*H*OH), 3.2 (br s, 1H, O*H*), 2.43–2.34 (m, 1H, C*H*CHOH), 2.26–2.19 (m, 1H, C*H*CHOH), 1.41 (d, *J* = 6.0 Hz, 3H, CH_3); ^{13}C NMR (125 MHz, $CDCl_3$), δ: 177.9, 75.2, 67.5, 37.1, 21.3; IR (film): 3383, 2983, 1769, 1128, 952; EIMS *m*/*z* (%) 117 ($[M+H]^+$) (2), 101 (3), 89 (8), 72 (15), 57 (100), 43 (41); HR-EIMS calcd for $C_4H_5O_3$ $(M-CH_3)^+$: 101.0239, found: 101.0242.

4.6. Synthesis of (2*S*,4*R*)-2-hydroxy-4-methyl-4-butanolide 10

The title product was obtained in the same manner as described for the preparation of (2*S*,4*S*)-2-hydroxy-4-methyl-4-butanolide **10**. (2*S*,4*S*)-**9** (50 mg; 0.21 mmol), yield 17 mg (70%) of (2*S*,4*R*)-**10** as an oil.

4.6.1. Analytical and spectral data for the compound (2*S*,4*R*)-10. Colorless oil; ^{1}H NMR (500 MHz, $CDCl_3$), δ: 4.56 (dd, *J* = 11.0, 8.3 Hz, 1H, C*H*OH), 4.55–4.48 (m, 1H, C*H*CH_3), 2.73 (ddd, *J* = 12.5, 8.3, 5.0 Hz, 1H, C*H*CHOH), 2.6 (br s, 1H, O*H*), 1.88 (ddd, *J* = 12.5, 11.0, 10.5 Hz, 1H, C*H*CHOH), 1.48 (d, *J* = 6.0 Hz, 3H, CH_3); ^{13}C NMR (125 MHz, $CDCl_3$), δ: 177.6, 73.7, 69.0, 38.7, 20.9; IR (film): 3386, 2982, 1769, 1389, 1205, 1132, 999, 945.

4.7. Synthesis of (2*S*,4*S*)-2-nitrobenzoyloxy-4-methyl-4-butanolide 11

Compound (2*S*,4*S*)-**10** (30 mg, 0.26 mmol) was dissolved in dry CH_2Cl_2 (2 mL) and then *p*-nitrobenzoyl chloride (120 mg, 0.65 mmol) added. The reaction mixture was cooled under argon to 0 °C and pyridine (0.06 mL, 0.71 mmol) added dropwise. After stirring at 0 °C for 10 min, the reaction mixture was allowed to reach room temperature, and stirring continued for an additional 1 h. Water (5 mL) was then added and the reaction mixture diluted with Et_2O (30 mL). The organic layer was washed with satd $NaHCO_3$ (3×20 mL), dried over $MgSO_4$, and concentrated in vacuo. Flash chromatography of the residue (hexane–ethyl acetate 85:15) of the residue afforded product **11** as white crystals (53 mg, 0.20 mmol, 77%). The product was recrystallized from the mixture of hexane and EtOAc.

4.7.1. Analytical and spectral data for the compound (2*S*,4*S*)-11. Mp 142–143 °C; $[\alpha]_D^{20} = -29.8$ (*c*, 1.07, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$), δ: 8.35–8.22 (m, 4H, Ph*H*), 5.72 (dd, *J* = 8.5, 7.5 Hz, 1H, C*H*OCOC_6H_4-NO_2), 4.98–4.87 (m, 1H, C*H*CH_3), 2.61–2.45 (m, 2H, CH_2CHOH), 1.51 (d, *J* = 6.5 Hz, 3H, CH_3), ^{13}C NMR (125 MHz, $CDCl_3$), δ: 171.9, 150.9, 134.1, 131.2, 132.7, 74.9, 69.4, 35.4, 21.6; IR (KBr): 3114, 1787, 1731,

1609, 1528, 1353, 1274, 1097, 719; LSIMS $(M)^+$: 553 $(2M+Na)^+$, 266 $(M+H)^+$; HR-LSIMS calcd for $C_{12}H_{12}O_6$ $(M+H)^+$: 266.06646, found: 266.06703.

4.8. Synthesis of (2*S*,4*R*)- and (2*S*,4*S*)-2-acetoxy-4-acetoxymethyl-4-butanolide 12

A mixture of adduct (2′*S*)-**3** (160 mg, 0.51 mmol), ammonium persulfate (351 mg, 1.54 mmol), and trifluoromethanesulfonic acid (0.14 mL, 1.54 mmol) in acetic acid (1.5 mL) was stirred at 70 °C for 3 h. The cooled mixture was poured into water and extracted with ethyl acetate (3 × 30 mL). The organic layers were combined, washed with satd $NaHCO_3$, dried over $MgSO_4$, and concentrated in vacuo. The resulting residue was purified by column chromatography on silica gel. Elution with hexane–ethyl acetate (8:2 → 7:3) gave a nonseparable mixture (1:1) of the diastereomers of **12** (77 mg, 0.35 mmol, 70%) as a colorless oil. (2*R*)-Bornane-10,2-sultam (44 mg, 0.20 mmol, 40%) and *N*-acetyl-(2*R*)-bornane-10,2-sultam (51 mg, 0.20 mmol, 40%) were also isolated after the chromatography.

4.8.1. Analytical and spectra data for compounds *cis*/*trans*-12.[12b,c] ^{1}H NMR (500 MHz, $CDCl_3$), δ: 5.55–5.45 (m, 2 × 1H, C*H*OAc, *cis* + *trans*), 4.92–4.86 (m, 1H, OC*H*CH_2OAc, *trans*), 4.72–4.65 (m, 1H, OC*H*-CH_2OAc, *cis*), 4.42–4.30 (m, 2 × 1H, CH_2OAc, *cis* + *trans*), 4.23–4.14 (m, 2 × 1H, CH_2OAc, *cis* + *trans*), 2.82–2.74 (m, 1H, CH_2CHOAc, *cis*), 2.63–2.53 (m, 1H, CH_2CHOAc, *trans*), 2.47–2.36 (m, 1H, CH_2CHOAc, *trans*), 2.18 (s, 3H, CH_3, *trans*), 2.17 (s, 3H, CH_3, *cis*), 2.13 (s, 3H, CH_3, *trans*), 2.12 (s, 3H, CH_3, *cis*), 2.12–2.02 (m, 1H, CH_2CHOAc, *cis*); ^{13}C NMR (125 MHz, $CDCl_3$), δ: 172.3, 171.6, 170.5, 170.3, 169.8, 169.7, 74.8, 74.0, 68.0, 67.5, 65.1, 64.3, 30.9, 30.7, 20.8, 20.7, 20.6; IR (CCl_4): 2961, 1808, 1754, 1453, 1374, 1227, 1187, 1169, 1105, 1047, 933, 843, 602; EIMS *m*/*z* (%): 217 ($[M+H]^+$, 0.5), 143 (7.6), 115 (8.8), 103 (7.6), 83 (4.7), 70 (7.0), 61 (4.7), 43 (100); LSIMS $(M)^+$:455 $(2M+Na)^+$, 433 $(2M+H)^+$, 239 $(M+Na)^+$, 217 $(M+H)^+$; HR-LSIMS calcd for $C_9H_{13}O_6$ $(M+H)^+$: 217.0712, found: 217.0708.

4.9. Synthesis of (2*S*,4*S*)-2-hydroxy-4-hydroxymethyl-4-butanolide 13

A suspension of $AgNO_2$ (0.5 g, 3.2 mmol) and compound (2*S*,4*R*)-**9** (121 mg, 0.5 mmol) in a mixture of EtOH–H_2O 10:1 (6 mL) was refluxed for 3 h. After filtering off the solid on Celite and washing with ethanol, the solution was concentrated in vacuo. Purification by column chromatography (ethyl acetate as eluent) afforded the compound **13** (30 mg, 0.23 mmol, 46%).

4.9.1. Analytical and spectral data for compound (2*S*, 4*S*)-13. Colorless oil; $[\alpha]_D^{20}$ = +18.7 (*c*, 0.76, MeOH); lit.[10] [α] = +23.2 (*c* 3.61, MeOH); ^{1}H NMR (500 MHz, CD_3OD), δ: 4.56 (dd, *J* = 10.7, 8.5 Hz, 1H, C*H*OH), 4.50–4.42 (m, 1H, C*H*CH_2OH), 3.80 (dd, *J* = 12.5, 5.3 Hz, CHC*H*OH), 3.59 (dd, *J* = 12.5, 5.3 Hz, 1H, CHC*H*OH), 2.53 (ddd, *J* = 11.7, 8.5, 5.8 Hz, 1H, C*H*CHOH), 1.98 (ddd, *J* = 11.7, 10.7, 10.7 Hz, C*H*CHOH), ^{13}C NMR (125 MHz, $CDCl_3$), δ: 179.1, 78.6, 69.3, 63.8, 33.6, EIMS *m*/*z* (%): 133 ($[M+H]^+$), 102 (26), 87 (11), 73 (100), 70 (20), 43 (13),LSIMS $(M)^+$: 265 $(2M+H)^+$, 133 $(M+H)^+$.

4.10. The X-ray structure investigations for compounds (2′*S*)-3 and (2*S*,4*S*)-11

The crystal data for both structures were measured on MACH3 κ-diffractometer using CuK_α radiation and ω–2θ scan mode. Structures were solved using direct

Table 4. Crystal data and structure refinement for compounds (2′*S*)-**3** and (2*S*,4*S*)-**11**

Identification code	(2′*S*)-**3**	(2*S*,4*S*)-**11**
Empirical formula	$C_{15}H_{23}NO_4S$	$C_{12}H_{11}NO_6$
Formula weight	313.40	265.22
Temperature (K)	293(2)	293(2)
Wavelength (Å)	1.54178	1.54178
Crystal system, space group	Orthorhombic, $P2_12_12_1$	Orthorhombic, $P2_12_12_1$
Unit cell dimensions (Å)	*a* = 8.115(2)	*a* = 7.7672(5)
	b = 12.7820(10)	*b* = 7.7585(14)
	c = 14.8690(10)	*c* = 23.147(6)
Volume (Å^3)	1542.3(4)	1394.9(4)
Z, calculated density (mg m^{-3})	4, 1.350	4, 1.263
Absorption coefficient (mm^{-1})	2.003	0.884
F(000)	672	552
Crystal size (mm)	0.7 × 0.35 × 0.15	0.35 × 0.35 × 0.18
Theta range for data collection	4.56–75.04	3.82–67.41
Index ranges	$-10 \leqslant h \leqslant 10$, $0 \leqslant k \leqslant 15$, $0 \leqslant l \leqslant 18$	$-7 \leqslant h \leqslant 0$, $-9 \leqslant k \leqslant 0$, $0 \leqslant l \leqslant 26$
Reflections collected/unique	1506/1506 [*R*(int) = 0.0000]	1199/1199 [*R*(int) = 0.0000]
Refinement method	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2
Data/restraints/parameters	1506/0/279	1199/0/173
Goodness-of-fit on F^2	1.055	1.095
Final *R* indices [$I > 2\sigma(I)$]	R_1 = 0.0430, wR_2 = 0.1174	R_1 = 0.0343, wR_2 = 0.0955
R indices (all data)	R_1 = 0.0441, wR_2 = 0.1190	R_1 = 0.0390, wR_2 = 0.1009
Absolute structure parameter	0.03(4)	−0.3(4)
Extinction coefficient	0.0006(4)	0.081(4)
Largest diff. peak and hole (e Å^{-3})	0.288 and −0.250	0.154 and −0.152

methods (SHELXS program) and refined using SHELX97 program. Table 4 shows details of data collection and structure refinement. Crystallographic data (excluding structure factors) have been deposited with Cambridge Crystallographic Data Centre as supplementary publication number CCDC 239175 for compounds (2′*S*)-**3** and number CCDC 239176 for compounds (2*S*,4*S*)-**11**. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44-1223-336033 or deposit@ccdc.cam.ac.uk).

References

1. For application of 2-hydroxypent-4-enoic acid and its esters, see: (a) Dauben, W. G.; Hendricks, R. T.; Pandy, B.; Wu, S. C. *Tetrahedron Lett.* **1995**, *36*, 2385–2388; (b) Rutjes, F. P. J.; Kooistra, T. M.; Hiemstra, H.; Schoemaker, H. S. *Synlett* **1998**, 192–194; (c) Macritchie, J. A.; Peakman, T. M.; Silcock, A.; Willis, C. L. *Tetrahedron Lett.* **1998**, *39*, 7415–7418.
2. For application of pent-4-ene-1,2-diol and its 1-monoprotected derivative, see: (a) Zemribo, R.; Mead, K. T. *Tetrahedron Lett.* **1998**, *39*, 3895–3898; (b) Díaz, Y.; Bravo, F.; Castillón, S. *J. Org. Chem.* **1999**, *64*, 6508–6511; (c) Ghosh, A. K.; Lei, H. *J. Org. Chem.* **2000**, *65*, 4779–4781.
3. Whitesell, J. K.; Bhattacharya, A.; Buchanan, C. M.; Chen, H. H.; Deyo, D.; James, D.; Liu, C.-L.; Minton, M. A. *Tetrahedron* **1986**, *42*, 2993–3001.
4. (a) Jung, J. E.; Ho, H.; Kim, H.-D. *Tetrahedron Lett.* **2000**, *41*, 1793–1796; (b) Yu, H.; Ballard, C. E.; Wang, B. *Tetrahedron Lett.* **2001**, *42*, 1835–1838.
5. (a) Macritchie, J. A.; Silcock, A.; Willis, C. L. *Tetrahedron: Asymmetry* **1997**, *8*, 3895–3902; (b) Loh, T.-P.; Xu, J. *Tetrahedron Lett.* **1999**, *40*, 2431–2434.
6. (a) Kiegiel, K.; Prokopowicz, P.; Jurczak, J. *Synth. Commun.* **1999**, *29*, 3999–4005; (b) Czapla, A.; Chajewski, A.; Kiegiel, K.; Bauer, T.; Wielogorski, Z.; Urbanczyk-Lipkowska, Z.; Jurczak, J. *Tetrahedron: Asymmetry* **1999**, *10*, 2101–2111; (c) Raszplewicz, K.; Sikorska, L.; Kiegiel, K.; Jurczak, J. *Pol. J. Chem.* **2002**, *76*, 1595–1600.
7. (a) Aoki, S.; Mikami, K.; Terada, M.; Nakai, T. *Tetrahedron* **1993**, *49*, 1783–1792; (b) Kwiatkowski, P.; Chaładay, W.; Jurczak, J. *Tetrahedron Lett.* **2004**, *45*, 5343–5346.
8. (a) Wang, D.; Wang, Z. G.; Wang, M. W.; Chen, Y. J.; Liu, L.; Zhu, Y. *Tetrahedron: Asymmetry* **1999**, *10*, 327–338; (b) Ramachandran, P. V.; Krzeminski, M. P.; Reddy, M. V. R.; Brown, H. C. *Tetrahedron: Asymmetry* **1999**, *10*, 11–15.
9. *Studies in Natural Products Chemistry*; Atta-ur-Rahman, Ed.; Elsevier: Amsterdam, 1995; Vol. 16.
10. Uchikawa, O.; Okukado, N.; Sakata, T.; Arase, K.; Terada, K. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 2025–2029.
11. Moriarty, R. M.; Kim, J.; Brumer, H., III. *Tetrahedron Lett.* **1995**, *36*, 51–54.
12. (a) Kučár, Š.; Zámocký, J.; Bauer, Š. *Collect. Czech. Chem. Commun.* **1975**, *40*, 457–461; (b) Bock, K.; Lundt, I.; Pedersen, C. *Acta Chem. Scand. B* **1981**, *35*, 155–162; (c) Okabe, M.; Sun, R.-C.; Zenchoff, G. B. *J. Org. Chem.* **1991**, *56*, 4392–4397; (d) Matsumoto, K.; Ebata, T.; Koseki, K.; Kawakami, K.; Okano, K.; Matsushita, H. *Heterocycles* **1992**, *34*, 363–367; (e) Choquet-Farnier, C.; Stasik, I.; Beaupère, D. *Carbohydr. Res.* **1997**, *303*, 185–191.
13. (a) Xie, Z.-F.; Sakai, K. *Chem. Pharm. Bull.* **1989**, *37*, 1650–1652; (b) Xie, Z.-F.; Suemune, H.; Sakai, K. *Tetrahedron: Asymmetry* **1993**, *4*, 973–980.
14. (a) Ticozzi, C.; Zanarotti, A. *Tetrahedron Lett.* **1994**, *35*, 7421–7424; (b) Enders, D.; Sun, H.; Leusink, F. R. *Tetrahedron* **1999**, *55*, 6129–6138.
15. (a) Bauer, T.; Chapuis, C.; Kozak, J.; Jurczak, J. *Helv. Chim. Acta* **1989**, *72*, 482–486; (b) Bauer, T.; Jeżewski, A.; Chapuis, C.; Jurczak, J. *Tetrahedron: Asymmetry* **1996**, *7*, 1385–1390.
16. (a) Whitesell, J. K.; Liu, C.-L.; Buchanan, C. M.; Chen, H.-H.; Minton, M. A. *J. Org. Chem.* **1986**, *51*, 551–553; (b) Ort, O. *Org. Synth.* **1987**, *65*, 203–214.
17. (a) Oppolzer, W.; Chapuis, C.; Bernardinelli, G. *Helv. Chim. Acta* **1984**, *67*, 1397–1401; (b) Oppolzer, W.; Poli, G.; Starkemann, C.; Bernardinelli, G. *Tetrahedron Lett.* **1988**, *29*, 3559–3562.
18. Curran, D. P.; Kim, B. H.; Daugherty, J.; Heffner, T. A. *Tetrahedron Lett.* **1988**, *29*, 3555–3558.
19. Bauer, T.; Chapuis, C.; Jezewski, A.; Kozak, J.; Jurczak, J. *Tetrahedron: Asymmetry* **1996**, *7*, 1391–1404.
20. For the previous works on the halolactonization of racemic 2-hydroxy-4-pentenoic acid, see: (a) Ohfune, Y.; Hori, K.; Sakaitani, M. *Tetrahedron Lett.* **1986**, *27*, 6079–6082; (b) Kitagawa, O.; Sato, T.; Taguchi, T. *Chem. Lett.* **1991**, 177–180.
21. (a) Bennett, F.; Bedford, S. B.; Bell, K. E.; Fenton, G.; Knight, D. W.; Shaw, D. *Tetrahedron Lett.* **1992**, *33*, 6507–6510; (b) Bedford, S. B.; Bell, K. E.; Bennett, F.; Hayes, C. J.; Knight, D. W.; Shaw, D. *J. Chem. Soc., Perkin Trans. 1* **1999**, 2143–2153.
24. (a) Fuji, K.; Node, M.; Naniwa, Y.; Kawabata, T. *Tetrahedron Lett.* **1990**, *31*, 3175–3178; (b) Yokomatsu, T.; Iwasawa, H.; Shibuya, S. *J. Chem. Soc., Chem. Commun.* **1992**, 728–729.
23. For previous works on the synthesis and stereochemistry of compounds **10**, see: (a) Arens, H.; Paetow, M.; Hoppe, D. *Tetrahedron Lett.* **1992**, *33*, 5327–5330; (b) Blandin, V.; Carpentier, J.-F.; Mortreux, A. *Tetrahedron: Asymmetry* **1998**, *9*, 2765–2768; (c) Blandin, V.; Carpentier, J.-F.; Mortreux, A. *Eur. J. Org. Chem.* **1999**, 1787–1893; (d) Bhalay, G.; Clough, S.; McLaren, L.; Sutherland, A.; Willis, C. L. *J. Chem. Soc., Perkin Trans. 1* **2000**, 901–910.
24. Collum, D. B.; McDonald, J. H., III; Still, W. C. *J. Am. Chem. Soc.* **1980**, *102*, 2118–2120.