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Dynamic Kinetic Resolution of Homoallylic Alcohols: Application to the Synthesis of Enantiomerically Pure 5,6-Dihydropyran-2-ones and δ-Lactones

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Abstract: Dynamic kinetic resolution of various homoallylic alcohols with the use of *Candida antarctica* lipase B and ruthenium catalyst **2** afforded homoallylic acetates in high yields and with high enantioselectivity. These enantiopure acetates were further transformed into homoallylic acrylates after hydrolysis of the ester function and subsequent DMAP-catalyzed esterification with acryloyl chloride. After ring-closing metathesis 5,6-dihydropyran-2-ones were obtained in good yields. Selective hydrogenation of the carbon–carbon double bond afforded the corresponding δ-lactones without loss of chiral information.

Keywords: dynamic kinetic resolution · homoallylic alcohols · lactones · racemization · ruthenium catalysis

Introduction

The δ-lactone ring is an important structural motif in organic chemistry since it is present in many natural products isolated from insects, plants, fungi and marine organisms (Figure 1).[1] The structure, synthesis and biological activity of many naturally occurring chiral lactone moieties have been described in the literature.[2] The unsaturated 5,6-dihydropyran-2-ones have been found to be cytotoxic,[3] they can inhibit HIV protease,[4] they can induce apoptosis,[5] and they have been shown to be antileukemic.[6] Some of these pharmacological effects can be explained by the presence of the conjugated carbon–carbon double bond, which can act as a Michael acceptor in biological systems. As a consequence, synthesis of these unsaturated lactones has attracted considerable attention. Recently, Marco et al. reviewed methods for stereoselective synthesis of naturally occurring 5,6-dihydropyran-2-ones.[7] Since variation of the substituents on these lactones has a potential impact on drug design, the development of new efficient strategies to generate skeletal diversity in these compounds is highly desirable in drug discovery.[8]

Enzyme-catalyzed kinetic resolution (KR) of a racemate has been shown to be an environmentally friendly and convenient technique for the separation of enantiomers. The major drawback of a KR is that the method only provides a maximum of 50% yield of the desired enantiomer in its optically pure form. This limitation can be circumvented by combining the enzymatic resolution with an in situ racemization of the two enantiomers, leading to dynamic kinetic resolution (DKR). DKR emerges over KR as a more powerful tool for the preparation of enantiomerically pure compounds, since the desired product can be obtained in a maximum yield of 100%.

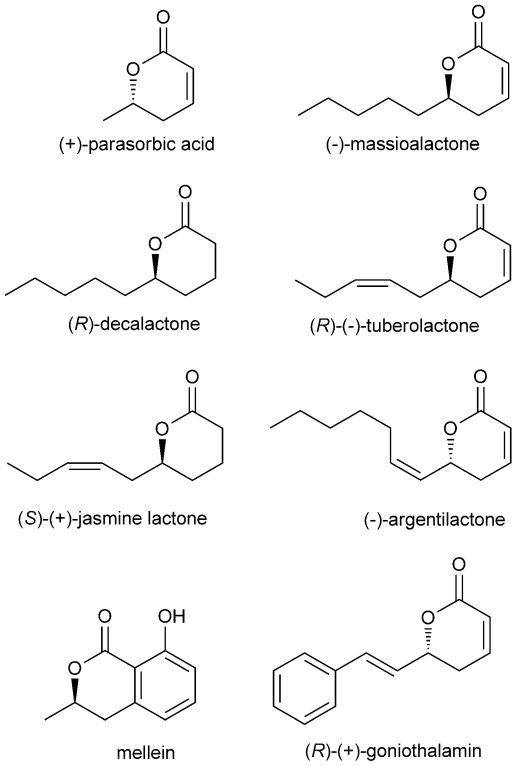

Figure 1. Some representative natural products containing a lactone moiety.

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A part of our research program focuses on the development of efficient DKR protocols for alcohols and amines to provide the corresponding enantiopure esters and amides. These products are highly valuable building blocks for asymmetric synthesis of structurally more complex molecules.[9,10] Initial work in the area was performed with Shvo's catalyst **1**, a dimeric Ru-based racemization catalyst used in combination with lipases (Figure 2).[11] More recently, our group

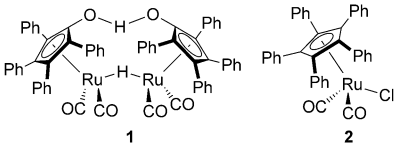


Figure 2. Ruthenium catalysts **1** and **2** utilized for racemization of *sec*-alcohols.

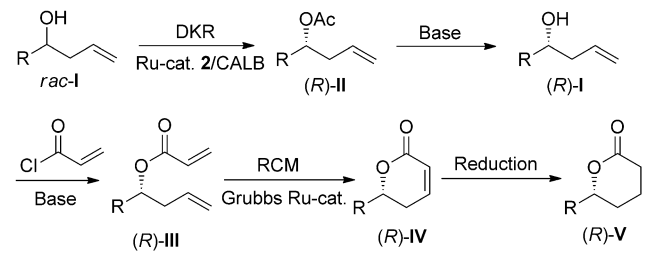
has developed a second generation ruthenium catalyst for the racemization of secondary alcohols, $[RuCl(CO)_2(\eta^5\text{-}C_5Ph_5)]$ (**2**; Figure 2).[12] Catalyst **2** has been utilized in combination with lipases in DKR of a wide range of substrates[13] and has successfully been scaled-up to >100 g scale.[14]

Homoallylic alcohols are common precursors for the synthesis of enantiomerically pure lactones.[15] The DKR of homoallylic alcohols has been studied previously. In 2011, the groups of Kanerva and Leino published the DKR of 1-phenyl-3-buten-1-ol, but the reaction required a very long time (168 h).[10c] Furthermore, Kim and Park reported on the DKR of a few homoallylic alcohols utilizing an ionic-surfactant-coated *Burkholderia cepacia* lipase (ISCBCL).[16] The method gave high yields and 95–98% *ee*.

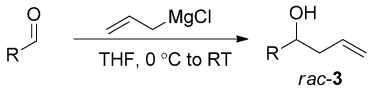
Herein we wish to report on an efficient DKR protocol for a wide range of homoallylic alcohol substrates. The corresponding esters were in many cases obtained in high yields and with excellent *ee* values. We also devised a general synthetic route for the enantioselective synthesis of 5,6-dihydropyran-2-ones and δ-lactones utilizing DKR of homoallylic alcohols in the enantiodetermining step. Our synthetic strategy begins with the DKR of various homoallylic alcohols, *rac*-**I**, which are transformed to the corresponding homoallylic esters (*R*)-**II** in high yields and with excellent enantioselectivity. After base hydrolysis the enantiopure homoallylic alcohols (*R*)-**I** obtained are allowed to react with acryloyl chloride providing acrylates (*R*)-**III**. These acrylates are further transformed into 5,6-dihydropyran-2-ones (*R*)-**IV** via ring-closing metathesis (RCM). Subsequent selective reduction of the carbon–carbon double bond affords the δ-lactones (*R*)-**V** in high yields with retained chiral information (Scheme 1).

Results and Discussion

Synthesis of homoallylic alcohol substrates: The homoallylic alcohol substrates **3a–n** were synthesized by addition of allylmagnesium chloride to commercially available aldehydes. Under standard conditions the Grignard reaction afforded a wide range of racemic homoallylic alcohols in high yields (Scheme 2; see the Supporting Information for further details and characterization).



Scheme 1. Synthetic strategy towards enantioenriched 5,6-dihydropyran-2-ones (*R*)-**IV** and δ-lactones (*R*)-**V** through DKR and subsequent RCM.



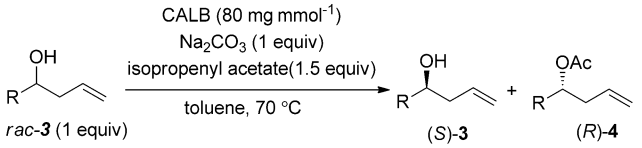
3a R = Ph (81%) **3b** R = 4-Me-Ph (78%) **3c** R = 4-MeO-Ph (84%) **3d** R = 4-F-Ph (86%) **3e** R = 4-Cl-Ph (79%) **3f** R = 4-Br-Ph (83%) **3g** R = 2-Me-Ph (89%) **3h** R = 1-naphthyl (82%) **3i** R = 2-naphthyl (83%) **3j** R = furane (100%) **3k** R = thiophene (100%) **3l** R = CH_2Ph (64%) **3m** R = (CH=CH)Ph (76%) **3n** R = $CH_3(CH_2)_6$ (76%)

Scheme 2. Synthesis of homoallylic alcohol substrates **3a–n**.

Enzymatic kinetic resolution of homoallylic alcohols: We first studied the enzymatic kinetic resolution of 1-phenyl-3-buten-1-ol (*rac*-**3a**) as model substrate with a variety of different commercially available homogeneous and immobilized lipases. The reactions were conducted in dry toluene at different temperatures (20, 40 and 70 °C). Out of the tested enzymes, immobilized *Burkholderia cepacia* lipase (previously *Pseudomonas cepacia* lipase) on ceramic particles, PS-C "Amano" I and PS-C "Amano" II and polymer supported *Candida antarctica* lipase B (CALB) showed the highest activity. When utilizing 80 mg mmol^{-1} of the immobilized enzyme together with isopropenyl acetate as acyl donor (1.5 equiv), the transesterification reaction became complete after 22 h at 70 °C (see the Supporting Information for further details). Since a highly enantioselective enzyme-catalyzed acylation is required for obtaining enantiomerically enriched products by DKR, we chose CALB for the enzymatic resolution and combined it with racemization catalyst **2**.

Next, the selectivity of the enzymatic reaction with CALB was investigated by calculating the *E* value at 70 °C for a few of the substrates (Table 1). As can be seen from the results, high *E* values were obtained, indicating a highly selective enzymatic resolution. The model substrate *rac*-**3a** showed the best selectivity giving an *E* value of >200 (Table 1, entry 1). A slightly lower selectivity was obtained with the introduction of a substituent on the aromatic ring

Table 1. Kinetic resolution of homoallylic alcohols *rac*-**2**.



Entry[a]	Substrate	t [h]	Conv. [%][b]	*ee* (*R*)-**4** [%][c]	E[d]
1	**3a**	2.5	47.0	>99	>200 (581)
2	**3b**	2.5	46.7	97	183
3	**3e**	2.5	42.3	98	>200 (211)

[a] Reaction conditions: *rac*-**3** (0.2 mmol), Na_2CO_3 (0.2 mmol), CALB (16 mg) and isopropenyl acetate (0.32 mmol) in dry toluene (0.4 mL) at 70 °C. [b] Determined by ^{1}H NMR spectroscopy. [c] Determined by chiral GC. [d] Calculated value.

(Table 1, entries 2 and 3), but the E values were still excellent.

Racemization of homoallylic alcohols: A racemization study on (*S*)-**3a** utilizing ruthenium complex **2** was also conducted in dry toluene at different temperatures (20, 40 and 70 °C) under inert atmosphere according to our standard conditions. The efficiency of the racemization was estimated with the $t_{1/2}$ value, which represents a drop of the *ee* of (*S*)-**3a** from 100 to 50 %. The racemization at 20 °C was not efficient enough since the *ee* of (*S*)-**3a** was still 63 % after 6 h. The slow racemization may be explained by coordination of the double bond of the homoallylic alcohol to ruthenium in the alkoxide intermediate thus blocking the coordination site required for β-hydride elimination.[17,18] At elevated temperatures the racemization rate increased and at 40 and 70 °C the $t_{1/2}$ values were 53 and 5 min, respectively (Figure 3). From these data we chose 70 °C as the temperature for the DKR.

Dynamic kinetic resolution of homoallylic alcohols: With the results from the separate investigations on the enzymatic resolution and the racemization in hand, their successful combination in a DKR was promising. DKR of homoallylic alcohols **3a–n** was performed on a 1 mmol scale, employing a 5 mol % loading of Ru-catalyst **2** at 70 °C (Table 2). In most cases the acylated products were obtained in good to excellent yields with high to excellent enantioselectivity. The products were isolated by column chromatography on silica.

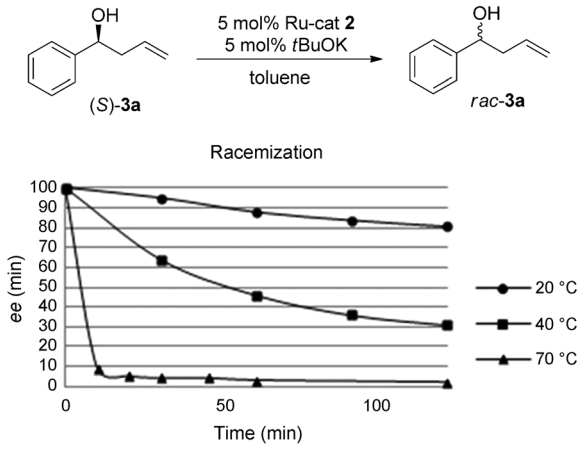


Figure 3. Racemization study on (*S*)-**3a** catalyzed by ruthenium complex **2**.

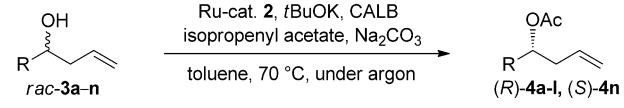
DKR of *rac*-**3a** afforded the corresponding enantiopure (*R*)-1-acetoxy-1-phenyl-3-butene [(*R*)-**3a**] in high yield and with excellent *ee* (Table 2, entry 1). This reaction was also run on a 5 mmol scale, which afforded an 84 % isolated yield of enantiopure product (*R*)-**3a**. Substituents in the *para*-position on the aromatic ring were shown to be compatible with the catalytic system (Table 2, entries 2–6). On the other hand substituents in the *ortho*-position were found to have a negative effect on both the racemization and the enzymatic resolution (Table 2, entries 7 and 8), most likely due to steric factors. Although the 1-naphthyl substrate **3h** was a very poor substrate (entry 8) the corresponding 2-naphthyl substrate **3i** gave a good yield in 96 % *ee* (entry 9). Electron-withdrawing substituents on the aromatic ring were compatible with the reaction conditions (Table 2, entries 4–6) but electron-donating substituents seemed to be moderately tolerated (Table 2, entry 3). For the *para*-methoxy substituted substrate *rac*-**3c**, the racemization was considerably slowed down due to the presence of the electron-donating substituent. Therefore, the enzyme loading was substantially decreased to provide a slower reaction, and hence a better match with the rate of racemization. This resulted in incomplete conversion but a good *ee* was obtained for this substrate (Table 2, entry 3). Interestingly, two heterocyclic substrates tested also showed high compatibility with this catalytic system (entries 10 and 11). For substrate *rac*-**3m**, which also contains an allylic functionality, the reaction was run at room temperature, which afforded the product (*R*)-**4m** in 63 % yield and with 98 % *ee* (Table 2, entry 13). In this reaction, 19 % of 4-oxo-6-phenyl-1-hexene was also obtained as a byproduct from isomerized starting material. Aliphatic substrates in which the small group is larger than ethyl and/or functionalized, generally show a very unselective enzymatic reaction.[13d] We were therefore pleased to find that a good result was obtained for the aliphatic substrate *rac*-**3n**, which afforded an 82 % isolated yield and 94 % *ee* of the product (*S*)-**4n** (Table 2, entry 14).

Synthetic applications: The 5,6-dihydropyran-2-ones [(*R*)-**6**] and δ-lactones [(*R*)-**7**] are readily accessible after a short reaction sequence as described in Scheme 3 for the transformation (*R*)-**4a** to (*R*)-**6a** and (*R*)-**7a**. Hydrolysis of acetate (*R*)-**4a** with K_2CO_3 in MeOH/H_2O (4:1) gave the enantiopure homoallylic alcohol (*R*)-**3a** in nearly quantitative yield. Subsequent DMAP-catalyzed acylation with acryloyl chloride and Et_3N afforded the corresponding acrylate (*R*)-**5a** in 81 % yield after purification by silica column chromatography. The ring-closing metathesis reaction proceeded well with Grubbs 1st generation catalyst (10 mol %) in dry DCM at 55 °C. The 5,6-dihydropyran-2-one (*R*)-**6a** was isolated in

high yield and with nearly retained enantiomeric excess after a short silica column. Selective reduction of the carbon–carbon double bond in (*R*)-**6a** was performed with Wilkinson's catalyst (2.5 mol%) and H_2 (1 atm) in dry toluene at room temperature, affording the δ-lactone (*R*)-**7a** in 85% yield and in 97% *ee* (Scheme 3).

The enantiomerically pure acetates (*R*)-**4b** and (*R*)-**4e** were transformed to the corresponding unsaturated lactones (*R*)-**6b** and (*R*)-**6e**, respectively (Scheme 4), following the hydrolysis-acylation-metathesis sequence (Scheme 3). The unsaturated lactones (*R*)-**6b** and (*R*)-**6e** were obtained in comparable yields and the *ee* in both cases was as that for (*R*)-**6a**. The yield of the last step and the *ee* of the unsaturated lactones are given in parenthesis in Scheme 4. The furan and thiophene lactones (*R*)-**6j** and **6k** are also accessible through the same approach. For these derivatives the acryloylation-metathesis sequence is described in ref. [15k] (Scheme 4). The synthetic sequence depicted in Scheme 3 can also be applied to synthetic intermediate (*R*)-**4m** leading to (*R*)-goniothalamin, a natural product with potential cytotoxic properties (Scheme 4).[19] The acryloylation-metathesis sequence to give (*R*)-**6m** is described in ref. [19].

Table 2. DKR of homoallylic alcohols **3a–n**.



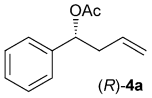
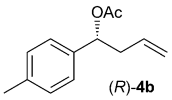
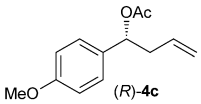
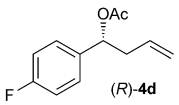
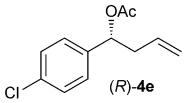
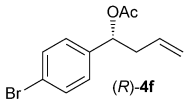
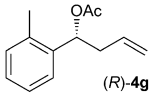
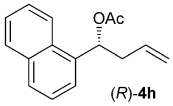
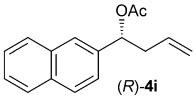
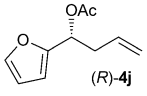
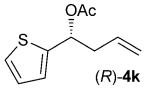
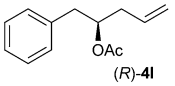
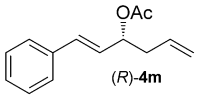
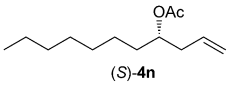
Entry[a]	Product	*t* [h]	Yield [%][b]	*ee* (*R*)-**4** [%][c]
1	 (*R*)-**4a**	24 12	99 (79) 99 (84)[d]	99 >99
2	 (*R*)-**4b**	24	99 (74)	98
3	 (*R*)-**4c**	48	65 (44)	94
4	 (*R*)-**4d**	24	99 (83)	>99
5	 (*R*)-**4e**	24	99 (86)	>99
6	 (*R*)-**4f**	24	99 (88)	>99
7	 (*R*)-**4g**	96	80	42
8	 (*R*)-**4h**	48	12	0
9	 (*R*)-**4i**	24	72	96
10	 (*R*)-**4j**	18	92	90
11	 (*R*)-**4k**	18	85	98
12	 (*R*)-**4l**	36	99 (86)	96

Table 2. (Continued)

Entry[a]	Product	*t* [h]	Yield [%][b]	*ee* (*R*)-**4** [%][c]
13[e]	 (*R*)-**4m**	96	63[f]	98
14[g]	 (*S*)-**4n**	22	82	94

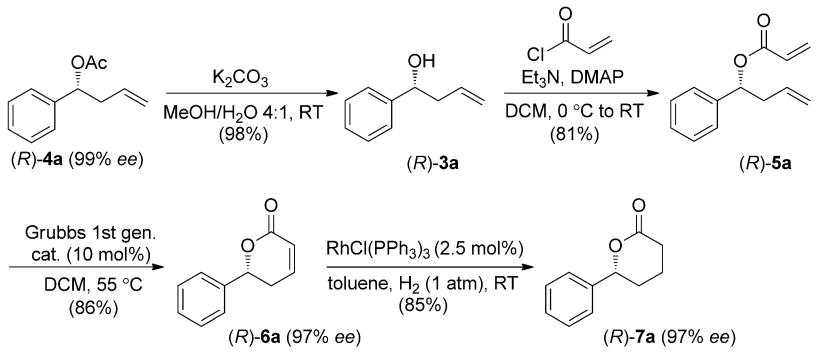
[a] Reaction conditions: $[Ru(CO)_2Cl(\eta^5\text{-}C_5Ph_5)]$ **2** (0.050 mmol), *t*BuOK (0.5 M solution in THF, 0.050 mmol), substrate *rac*-(**3**) (1 mmol), CALB (10–100 mg mmol^{-1}), Na_2CO_3 (1 mmol) and isopropenyl acetate (1.5 mmol) in dry toluene (2 mL) heated to 70 °C under argon. [b] Determined by ^{1}H NMR spectroscopy. Isolated yield after chromatography in parentheses. [c] Determined by chiral GC or HPLC. [d] 5 mmol scale. [e] The reaction was run at room temperature. [f] 19% of 4-oxo-6-phenyl-1-hexene was obtained as a byproduct from isomerized starting material. [g] *R* changes to *S* because of the sequential rule.

Conclusion

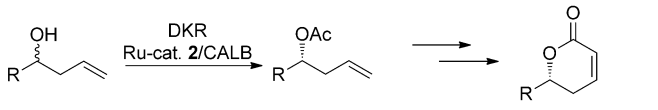
In summary, we have developed an efficient DKR protocol for a wide range of homoallylic alcohol substrates, utilizing ruthenium catalyst **2** for the racemization and CALB for the enzymatic resolution. The corresponding acetates were obtained in good to high yields and with high to excellent *ee* values. The catalytic system was found to be applicable to aromatic substrates and worked well with both electron-deficient and electron-rich aromatic rings. The reaction was also shown to work for two heterocyclic substrates and for one aliphatic substrate. The synthetic utility of the products obtained from the DKR was demonstrated by a short reaction sequence leading to biologically important 5,6-dihydropyran-2-ones and the corresponding δ-lactones with nearly retained chiral information.

Experimental Section

General procedure for dynamic kinetic resolution of homoallylic alcohols *rac*-3: $[(\eta^5\text{-}Ph_5C_5)Ru(CO)_2Cl]$ (**2**; 5.0 mol%), Na_2CO_3 (1 equiv) and



Scheme 3. Synthetic reaction sequence affording 5,6-dihydropyran-2-one (*R*)-**6a** and δ-lactone (*R*)-**7a**.



R = Ph, *rac*-**3a**	(*R*)-**4a** (84%, 99% *ee*)	(*R*)-**6a** (86%, 97% *ee*)
R = 4-Me-Ph, *rac*-**3b**	(*R*)-**4b** (74%, 98% *ee*)	(*R*)-**6b** (82%,98% *ee*)
R = 4-Cl-Ph, *rac*-**3e**	(*R*)-**4e** (86%, 99% *ee*)	(*R*)-**6e** (87%, 98% *ee*)
R = furane, *rac*-**3j**	(*R*)-**4j** (92%, 90% *ee*)	(*R*)-**6j** (ref. [15k])
R = thiophene, *rac*-**3k**	(*R*)-**4k** (85%, 98% *ee*)	(*R*)-**6k** (ref. [15k])
R = (CH=CH)-Ph, *rac*-**3m**	(*R*)-**4m** (63%, 98% *ee*)	(*R*)-**6m** (ref. [19])

Scheme 4. Synthetic reaction sequence affording 5,6-dihydropyran-2-ones (*R*)-**6**.

CALB (10–100 mg mmol^{-1}) were added to a dry Schlenck flask. The flask was back-flushed with argon and dry toluene (1.0 mL) was added. *t*BuOK (100 μL of a 0.5 M solution in THF, 5.0 mol%) was then added and the reaction was stirred and heated to 70 °C. Compound *rac*-**3** (1.0 mL of a 1.0 M solution in toluene, 1 equiv) was added after 5 min. After an additional 4 min, isopropenyl acetate (170 μL, 1.5 mmol, 1.5 equiv) was added. When complete, the reactions were quenched by filtration through a short pad of silica with EtOAc. The crude products were purified by flash chromatography (5% EtOAc in pentane).

Hydrolysis of acetate (*R*)-4a: Acetate (*R*)-**4a** (0.240 g, 1.27 mmol) was dissolved in a MeOH/H_2O 4:1 (25 mL) at room temperature. K_2CO_3 (0.50 g, 3.6 mmol) was added in one portion and the mixture was stirred at room temperature for 2 h. The reaction was then quenched by the addition of $NaHCO_3$ (1.0 g, 12 mmol). The MeOH was evaporated and the remaining aqueous layer was extracted with EtOAc (3×50 mL). The combined organic layer was washed with saturated aqueous $NaHCO_3$ (1×50 mL) and brine (1×50 mL), dried over $MgSO_4$, and filtered. Solvent evaporation afforded the crude product (*R*)-**3a** as a colorless oil in nearly quantitative yield (0.18 g, 1.24 mmol, 98%). The crude product was used without further purification. Spectral data for homoallylic alcohol **3a** was in accordance with the literature for the racemic compound.[20] ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.38–7.34 (m, 4H), 7.30–7.27 (m, 1H), 5.86–5.78 (m, 1H), 5.19–5.14 (m, 2H), 4.76–4.73 (m, 1H), 2.57–2.47 (m, 2H), 2.03–2.02 ppm (d, J = 3.3 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 144.0, 134.6, 128.6, 127.7, 125.9, 118.6, 73.4, 44.0 ppm.

Synthesis of acrylate (*R*)-5a: (*R*)-**3a** (0.18 g, 1.24 mmol) was dissolved in dry DCM (10 mL) and DMAP (one crystal), Et_3N (0.19 mL, 1.4 mmol) and acryloyl chloride (0.12 mL, 1.5 mmol) were added at 0 °C. The solution was stirred under argon atmosphere at room temperature for 24 h. The reaction was quenched by addition of saturated aqueous $NaHCO_3$ and the layers were separated. The organic phase was washed with saturated aqueous $NaHCO_3$ (2×50 mL) and brine (1×50 mL), dried over $MgSO_4$, filtered and evaporated. The crude product was purified by flash chromatography (5% EtOAc in pentane), affording the pure product (*R*)-**5a** as a colorless oil in 81% yield. Spectral data were in accordance with the racemic compound, *rac*-**5a**.[21] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.36–7.27 (m, 5H), 6.45–6.40 (dd, 1H, J = 17.4 and 1.5 Hz), 6.19–6.12 (dd, 1H, J = 17.4 and 10.4 Hz), 5.91–5.87 (dd, 1H, J = 7.6 and 6.0 Hz), 5.85–5.82 (dd, 1H, J = 10.4 and 1.5 Hz), 5.77–5.67 (m, 1H), 5.11–5.04 (m, 2H), 2.74–2.67 (m, 1H), 2.64–2.58 ppm (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 165.5, 140.1, 133.4, 131.0, 128.8, 128.6, 128.1, 126.7, 118.3, 75.5, 40.9 ppm.

Synthesis of 5,6-dihydropyran-2-one (*R*)-6a: The substrate (*R*)-**5a** (0.072 g, 0.36 mmol) was dissolved in dry DCM (50 mL) and stirred under an argon atmosphere. Grubbs 1st generation catalyst (0.029 g, 0.036 mmol, 10 mol%) was added dropwise dissolved in dry DCM (5 mL). The resulting solution was refluxed under argon atmosphere, overnight. When TLC analysis indicated that the starting material was fully consumed, the solvent was evaporated. The crude product was purified by flash chromatography (5% EtOAc in pentane to 50% EtOAc in pentane). The pure product (*R*)-**6a** was obtained in 86% yield (0.054 g, 0.31 mmol) and with 97% *ee*. Spectral data were in accordance with the literature for the racemic compound, *rac*-**6a**.[22] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43–7.34 (m, 5H), 6.99–6.95 (ddd, 1H, J = 9.8, 5.5 and 2.8 Hz), 6.17–6.13 (ddd, 1H, J = 9.8, 2.8 and 1.2 Hz), 5.48–5.44 (dd, 1H, J = 4.9 and 11.0 Hz), 2.72–2.59 ppm (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.2, 145.0, 138.6, 128.8, 128.7, 126.2, 121.9, 79.4, 31.8 ppm.

Synthesis of δ-lactone (*R*)-7a: The substrate (*R*)-**6a** (0.029 g, 0.17 mmol) was dissolved in dry toluene (2.0 mL) and [$RhCl(PPh_3)_3$] (0.0038 g, 0.004 mmol, 2.5 mol%) was added. The reaction was stirred under H_2 atmosphere (1 atm) at room temperature for 48 h. The reaction mixture was then filtered through Celite with EtOAc and evaporated. The crude product was purified by flash chromatography (5% EtOAc in pentane to 50% EtOAc in pentane). The pure product (*R*)-**7a** was obtained in 85% yield (0.025 g, 0.14 mmol) and with 97% *ee*. Spectral data were in accordance with the literature.[15m] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43–7.33 (m, 5H), 5.40–5.37 (dd, 1H, J = 10.5 and 3.6 Hz), 2.78–2.70 (m, 1H), 2.65–2.56 (m, 1H), 2.24–2.17 (m, 1H), 2.05–1.98 (m, 2H), 1.95–1.85 ppm (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 171.3, 139.8, 128.6, 128.3, 125.7, 81.6, 30.5, 29.5, 18.6 ppm.

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