



Cite this: *RSC Adv.*, 2022, 12, 16576

Received 7th May 2022
Accepted 26th May 2022

DOI: 10.1039/d2ra02891c

rsc.li/rsc-advances

Total syntheses of *ent*-hypocoprins A and *ent*-hypocoprins B†

Koichiro Ota, * Taiki Watanabe, Shuntaro Igarashi, Shinnosuke Okazaki, Kazuo Kamaike and Hiroaki Miyaoka *

This study reports the stereoselective total syntheses of the antipodes of the unique 3/10 bicyclic skeletal sesquiterpenoids, namely, hypocoprins A and hypocoprins B. The synthesis involved conjugate addition accelerated by trimethylsilyl chloride, construction of the ten-membered ring via the intramolecular S_N2 reaction promoted by 1,8-diazabicyclo[5.4.0]undec-7-ene, and osmium-mediated π -facial selective dihydroxylation to functionalize the 1,1-disubstituted alkene.

Introduction

Hypocoprins A and hypocoprins B, isolated from the coprophilous fungus *Hypocopra rostrata* on horse dung, are sesquiterpenoids with an unprecedented 3/10 bicyclic ring system (Fig. 1).¹ The 3/10 bicyclic scaffold of these sesquiterpenoids is thought to arise biosynthetically by 8,11-cyclization of the *trans*-humulyl cation derived from farnesyl diphosphate. The only other examples with the same scaffold are the marine diterpenoid palmato² (from the Mediterranean octocoral *Alcyonium palmatum*) and pacificins^{3,4} (from the Formosan soft coral *Nephthea* sp.). Consequently, the biosynthetic origins of the bicyclic system in hypocoprins are largely unknown. Hypocoprins A moderately inhibits the growth of the Gram-positive bacteria *Staphylococcus aureus* and *Bacillus subtilis* but is ineffective against *Candida albicans* or the Gram-negative bacterium *Escherichia coli*.¹ To explore the unreported biological properties of hypocoprins A and B with novel bicyclic scaffolds, we describe novel total syntheses of *ent*-hypocoprins A (1) and *ent*-hypocoprins B (2) starting from the optically active acetonide 3.

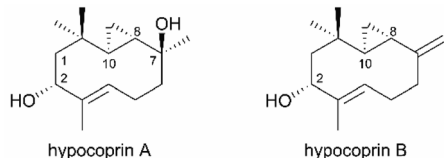


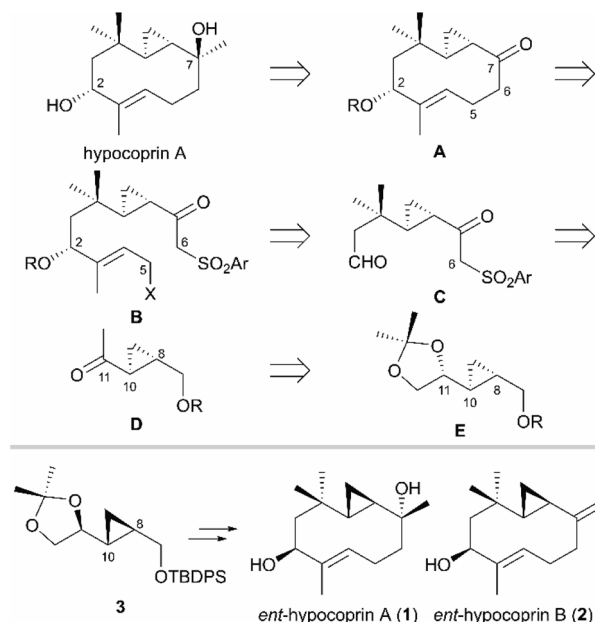
Fig. 1 Structures of natural hypocoprins A and hypocoprins B.

School of Pharmacy, Tokyo University of Pharmacy and Life Sciences, 1432-1 Horinouchi, Hachioji, Tokyo 192-0392, Japan. E-mail: otak@toyaku.ac.jp; miyaoka@toyaku.ac.jp

† Electronic supplementary information (ESI) available. CCDC 2150062. For ESI and crystallographic data in CIF or other electronic format see <https://doi.org/10.1039/d2ra02891c>

Results and discussion

Our retrosynthetic analysis of hypocoprins A is depicted in Scheme 1. In the initial planning stage, we recognized that the C-7 tertiary alcohol moiety can be constructed in hypocoprins A via diastereoselective addition of the C₁-unit to bicyclic ketone A. We thus planned the synthesis of bicyclic ketone A with a core ten-membered ring from β -ketosulfone B via an intramolecular S_N2 reaction followed by reductive desulfonation. We assumed that β -ketosulfone B would arise from the chemoselective addition of a vinyl lithium species to ketoaldehyde C and the introduction of a halogen (X) atom. The β , β -



Scheme 1 Retrosynthetic analysis of *ent*-hypocoprins A (1) and *ent*-hypocoprins B (2).



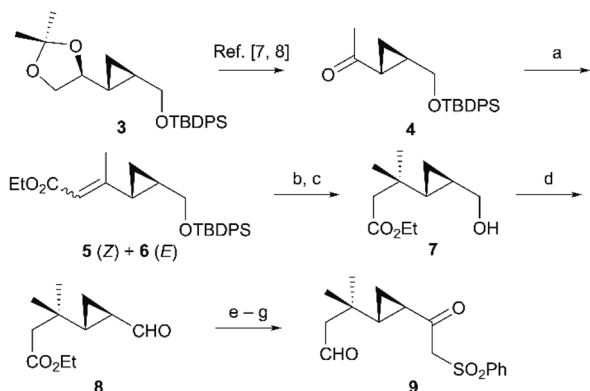
disubstituted aldehyde moiety in β -ketosulfone **9** can be constructed by the Horner–Wadsworth–Emmons homologation of cyclopropyl ketone **4** followed by conjugate addition with an organocopper reagent. Cyclopropyl ketone **4** can be obtained from acetonide **3**, which possesses C-8 and C-10 stereochemistry established by substrate-controlled stereoselective cyclopropanation. We established a synthetic route for the antipodes of hypocoprins **A** and **B** from acetonide **3**, which corresponds to the enantiomer of acetonide **3** synthesized from D-mannitol, an inexpensive and ideal chiral pool for total synthesis. The total syntheses of *ent*-hypocoprins **A** (**1**) and *ent*-hypocoprins **B** (**2**) were initiated from acetonide **3** via a retrosynthetic analysis.

Our synthesis commenced from acetonide **3** (>97% ee),⁵ a known enantiopure compound prepared from D-mannitol (Scheme 2).⁶ After sequential acidic deprotection of the isopropylidene group of **3** and oxidative cleavage with periodic acid,⁷ the aldehyde was methylated with MeMgBr and the resulting secondary alcohol was oxidized with 2-iodoxybenzoic acid (IBX) to afford cyclopropyl ketone **4**.⁸ C₂-Homologation of cyclopropyl ketone **4** by the Horner–Wadsworth–Emmons reaction afforded α,β -unsaturated esters **5** and **6** in 95% yield (*E* : *Z* = 9 : 1). We next examined various conditions for the conjugate addition of **5** and **6**, but unexpectedly, the starting material was recovered with only trace amounts of the desired adducts, presumably because the conjugate addition of organocopper reagents was inhibited by steric hindrance of the adjacent cyclopropyl group. To improve the reactivity, we extensively screened the solvents, temperatures, and addition of Lewis acid. The conjugate addition proceeded efficiently under a combined lithium dimethylcuprate–chlorotrimethylsilane reagent⁹ in CH₂Cl₂/Et₂O followed by desilylation, delivering primary alcohol **7** in high yields (85% overall yield over two steps). IBX oxidation converted the primary alcohol **7** into aldehyde **8** (88% yield). Aldehyde **8** was subsequently treated with the α -sulfonyl carbanion derived from methyl phenyl sulfone and butyllithium (BuLi), providing secondary alcohols as a diastereomeric mixture. The resulting alcohols were

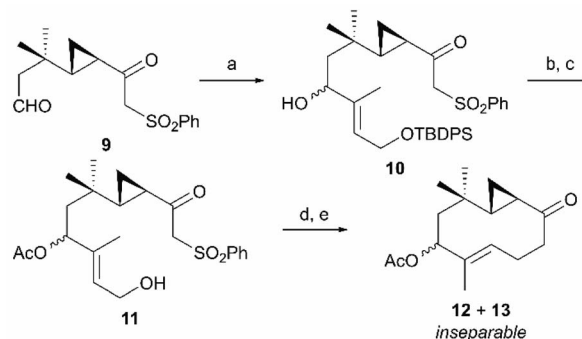
reduced with diisobutylaluminum hydride (DIBALH) followed by oxidation with IBX to give β -ketosulfone **9** (77% overall yield over three steps).

Having obtained β -ketosulfone **9**, which corresponds to the retrosynthetic intermediate **C** shown in Scheme 1, we introduced a trisubstituted alkene moiety followed by cyclization of the ten-membered ring (Scheme 3). The trisubstituted alkene moiety was introduced to β -ketosulfone **9** by aldehyde-selective addition of the vinyl lithium species derived from (*E*)-*tert*-butyl((3-iodobut-2-en-1-yl)oxy)diphenylsilane¹⁰ and ^tBuLi, forming the secondary alcohol **10** as a pair of inseparable diastereomers (79% yield, dr = 1 : 1). After acetylating the secondary alcohol **10**, primary alcohol was selectively unmasked to allylic alcohol **11** (89% overall yield over two steps), which was converted to allylic bromide with CBr₄ and Ph₃P. The resulting allylic bromide was an important precursor for cyclizing the ten-membered ring, but was unstable. Therefore, after confirming the disappearance of the starting material by thin-layer chromatography, we immediately added 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU). To our delight, the intramolecular S_N2 alkylation proceeded smoothly, followed by SmI₂-mediated reductive desulfonation¹¹ to give a pair of ten-membered cyclic ketones (**12** and **13**) as an inseparable diastereomeric mixture (76% overall yield over two steps).

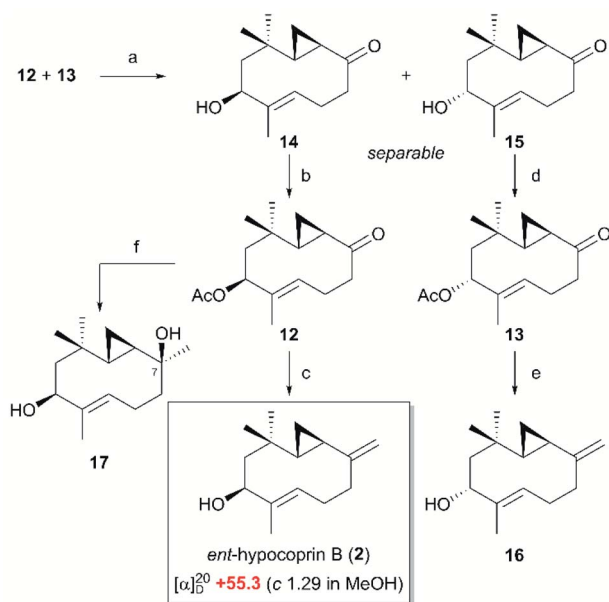
The ten-membered cyclic ketones **12** and **13** were deacetylated and separated as secondary alcohols **14** and **15**, respectively, and then re-acetylated to give ketones **12** and **13** as single stereoisomers (Scheme 4). The ten-membered cyclic ketones **12** and **13** were exposed to Wittig methylenation, providing the *exo*-olefins **2** and **16** in 92% and 90% yield, respectively. Comparing the ¹H and ¹³C NMR spectral data of the *exo*-olefins **2** and **16** with the reported data, the NMR spectrum of **2** was found to be consistent with that of natural hypocoprins **B**.¹ However, whereas the specific rotation should be opposite to that of natural hypocoprins **B** ([α]_D²⁰ +13 (c 0.58 in MeOH)),¹ it was instead consistent with that of synthesized **2** ([α]_D²⁰ +55.3 (c 1.29 in MeOH)). In the previous isolation paper,¹ the absolute configuration of natural hypocoprins **B** was determined by conversion



Scheme 2 Synthesis of aldehyde **9**. Reagents and conditions (a) (EtO)₂POCH₂CO₂Et, NaH, toluene, reflux, 95% (*E* : *Z* = 9 : 1); (b) MeLi, CuI, TMSCl, CH₂Cl₂, Et₂O, 0 °C; (c) TBAF, THF, r.t., 85% (2 steps); (d) IBX, DMSO/THF, r.t., 88%; (e) MeSO₂Ph, BuLi, THF, −78 °C; (f) DIBALH, CH₂Cl₂, −78 °C; (g) IBX, DMSO/THF, r.t., 77% (3 steps).



Scheme 3 Closure of the ten-membered ring via the intramolecular S_N2 reaction. Reagents and conditions (a) (*E*)-*tert*-butyl((3-iodobut-2-en-1-yl)oxy)diphenylsilane, ^tBuLi, THF/Et₂O, −78 °C, 79% (dr = 1 : 1); (b) Ac₂O, pyridine, r.t.; (c) TBAF, THF, r.t., 89% (2 steps); (d) CBr₄, Ph₃P, CH₂Cl₂, 0 °C then DBU, benzene, 0 °C to r.t.; (e) SmI₂, THF, 0 °C, 76% (2 steps).



Scheme 4 Synthesis of *ent*-hypocoprins B (2) and 7-*epi-ent*-hypocoprins A (17). Reagents and conditions (a) K_2CO_3 , MeOH, r.t., 14 48%, 15 46%; (b) Ac_2O , pyridine, r.t., 96%; (c) Ph_3PCH_3Li , BuLi, THF, r.t., 99%; (d) Ac_2O , pyridine, r.t., 95%; (e) Ph_3PCH_3Li , BuLi, THF, r.t., 90%; (f) MeLi, Et_2O/THF , 0 °C, 95%.

from hypocoprins A, whose absolute configuration was determined by the Mosher method. Therefore, withholding our doubts on stereochemistry at this stage, we continued with the synthesis of *ent*-hypocoprins A (1). Toward the completion of the total synthesis of *ent*-hypocoprins A (1), we first attempted a direct nucleophilic addition of MeLi to the intermediate ten-membered cyclic ketone 12, obtaining the tertiary alcohol 17 as a single diastereomer in 98% yield. Unfortunately, the 1H and ^{13}C NMR spectra of 17 were inconsistent with those of natural hypocoprins A.¹ Although the relative configuration of 17 could not be determined by nuclear Overhauser effect (NOE) spectroscopy, most of the substrate was converted to *ent*-hypocoprins B (2) by dehydration during three-weeks' storage of 17 in $CDCl_3$. Consequently, compound 17 was inferred as the C-7 epimer of *ent*-hypocoprins A (1).

The exclusive diastereoselectivity of alkylation was attributable to steric congestion inside the ten-membered ring. We then estimated the conformation of *ent*-hypocoprins B (2) based on the observed NOE correlations (Fig. 2a). The results suggested that the C-3/C-13 single bond and the C-7/C-12 double bond are approximately perpendicular to the average plane of the ten-membered ring in the same direction, whereas the C-3/C-4 double bond and the C-8/C-10 single bond preferentially face each other in parallel across the ten-membered ring. That is, the C-3/C-4 and C-7/C-12 double bonds are clearly distinguished inside and outside the ten-membered ring, suggesting the feasibility of a π -facial selective approach to alkene moieties.

Diene 18 obtained by acetylation of *ent*-hypocoprins B (2) was subjected to osmium-mediated dihydroxylation using AD-mix-

(a) Selected NOE correlations for *ent*-hypocoprins B (2)

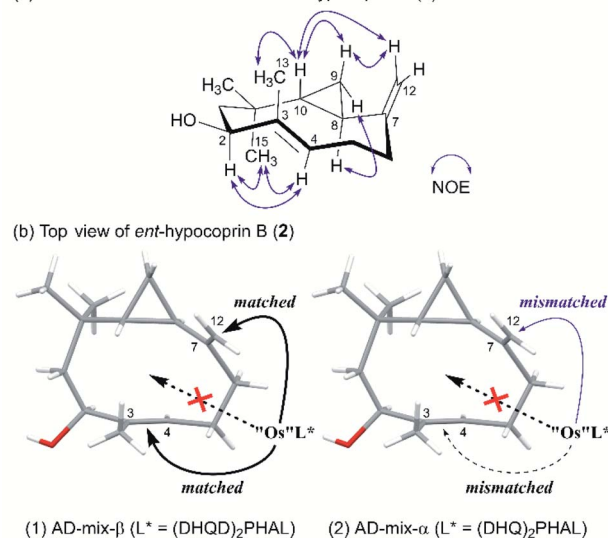
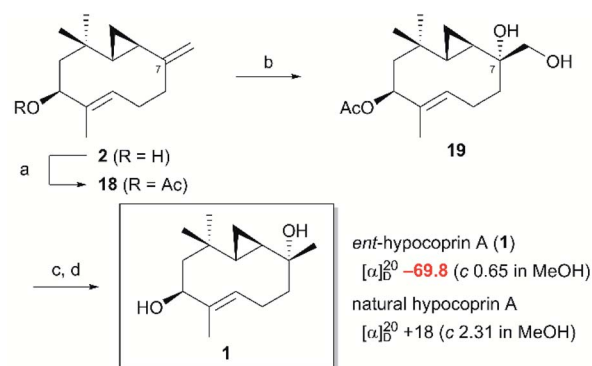


Fig. 2 Plausible mechanism of osmium-mediated π -facial selective dihydroxylation. (a) Selected NOE correlations for *ent*-hypocoprins B (2). (b) Top view of *ent*-hypocoprins B (2).

α or AD-mix- β (Scheme 5).^{12,13} In dihydroxylation using AD-mix- β , diene 18 was converted to completely unrecoverable high-polarity compounds within six hours. However, when AD-mix- α was attempted, the starting material 18 disappeared after around 24 hours, yielding the desired stereoisomer 19 with complete selectivity for C-7 as a mixture with $MeSO_2NH_2$. The stereochemistry of C-7 after derivatization to *ent*-hypocoprins A (1) was determined by X-ray crystallography. Interestingly, the C-3/C-4 trisubstituted alkene moiety was unaffected during this reaction. To understand this ideal π -facial selectivity, we employed a mnemonic device for predicting the stereoselectivity of dihydroxylation using AD-mix. The two alkene moieties of 18 were considered individually because they belong to different alkene-substitution classes. Considering the trisubstituted alkene (C-3/C-4) moiety, AD-mix- β and AD-mix-



Scheme 5 Completion of the total synthesis of *ent*-hypocoprins A (1). Reagents and conditions (a) Ac_2O , pyridine, r.t.; (b) AD-mix- α , $MeSO_2NH_2$, $^tBuOH/H_2O$, 0 °C; (c) $pTsCl$, pyridine, 30 °C; (d) $LiEt_3BH$, THF, r.t., 94% (4 steps).



α are expected to preferentially proceed from outside and inside the ten-membered ring, respectively (Fig. 2b). As mentioned in Scheme 4, the inside is sterically congested, so dihydroxylation was unlikely to proceed in the presence of AD-mix- α . In contrast, 1,1-disubstituted alkene (C-7/C-12) moiety and AD-mix- β are undoubtedly a “matched” pair for dihydroxylation proceeding from outside the ring, as evidenced by the short reaction time. Nevertheless, AD-mix- α satisfactorily mediated the stereospecific dihydroxylation despite being mismatched for dihydroxylation proceeding from the outside. As is well known, the stereoselectivity of dihydroxylation is lower for 1,1-disubstituted alkenes than for trisubstituted alkenes.¹⁴ We thus hypothesized that the present regio- and diastereoselective dihydroxylations resulted from a combination of strict recognition of trisubstituted alkenes and permissive recognition of 1,1-disubstituted alkenes. Subsequently, monotosylation of diol **19**, followed by reductive hydrogenation of the resulting tosylate with lithium triethylborohydride,¹⁵ led to *ent*-hypocoprins A (**1**). Compound **1** presented the same ¹H NMR, ¹³C NMR, and high-resolution mass spectra as natural hypocoprins A but its specific rotation was opposite in sign [α]_D²⁰ −69.8 (*c* 0.65 in MeOH) to that of natural hypocoprins A (ref. 1 [α]_D²⁰ +18 (*c* 2.31 in MeOH)). Furthermore, the relative configuration of synthetic compound **1** was confirmed by single-crystal X-ray diffraction (Fig. 3).¹⁶

As expected, the specific rotation of the synthesized *ent*-hypocoprins A (**1**) was opposite in sign to that of natural hypocoprins A but the values of the two compounds were quite different. Many signals in the reported NMR spectrum of natural hypocoprins A were derived from impurities (mainly hypocoprins B), so the accuracy of the reported specific rotation was doubtful. In addition, as the sign of the synthesized *ent*-hypocoprins B (**2**) matched that of the reported specific rotation of hypocoprins B, one or both of the reported specific rotations might be incorrect. Therefore, we should not conclude that the synthesized *ent*-hypocoprins A (**1**) is a natural antipode only because the sign of its specific rotation is reversed. To confirm the correctness of the reported absolute configuration of hypocoprins A, we compared the NMR spectra of α -methoxy- α -trifluoromethylphenylacetic acid (MTPA) ester derivatives. In a previous study, the absolute configuration of natural hypocoprins A was determined by assigning the stereocenter of C-2 by the Mosher method.^{1,17,18}

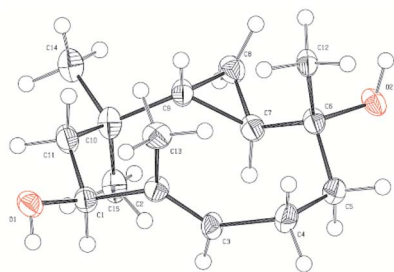


Fig. 3 Oak Ridge Thermal Ellipsoid Plot (ORTEP) of *ent*-hypocoprins A (**1**).

Therefore, *ent*-hypocoprins A (**1**) was converted into (*R*)-MTPA and (*S*)-MTPA esters and their NMR spectra were obtained. The spectra were consistent with the (*S*)-MTPA and (*R*)-MTPA esters of natural hypocoprins A described in the isolation paper. Therefore, one may reasonably conclude that the absolute configuration of the natural product reported in the isolation paper is correct.

Conclusions

In summary, we have accomplished a novel asymmetric total synthesis of *ent*-hypocoprins A (**1**) from optically active ketone **4** (19 steps, 13% overall yield). The key steps of our synthesis were TMSCl-accelerated conjugate addition, DBU-promoted cyclization to form the ten-membered ring, and osmium-mediated dihydroxylation under “mismatched” conditions to furnish the antipodes of the unique bicyclic sesquiterpenoids hypocoprins A and B. The biological activity of the two synthesized antipodes is currently under investigation. Moreover, we are applying our synthetic strategy to other unexplored 3/10 bicyclic sesquiterpenoids and diterpenoids.

Conflicts of interest

There are no conflicts to declare.

Notes and references

- 1 D. R. Jayanetti, Q. Yue, G. F. Bills and J. B. Gloer, *J. Nat. Prod.*, 2015, **78**, 396.
- 2 E. Zubia, A. Spinella, G. B. Guisto, A. Crispino and G. Cimino, *Tetrahedron Lett.*, 1994, **35**, 7069.
- 3 A. A. H. El-Gamal, S.-K. Wang, C.-F. Dai, I.-G. Chen and C.-Y. Duh, *J. Nat. Prod.*, 2005, **68**, 74.
- 4 A. A. H. El-Gamal, S.-K. Wang and C.-Y. Duh, *Chem. Pharm. Bull.*, 2007, **55**, 890.
- 5 The specific rotation of acetone **3** was [α]_D²⁷ −7.7 (*c* 1.07 in CHCl₃) (ref. 6 [α]_D²⁷ −7.9 (*c* 1.15 in CHCl₃)).
- 6 T. Morikawa, H. Sasaki, R. Hanai, A. Shibuya and T. Taguchi, *J. Org. Chem.*, 1994, **59**, 97.
- 7 J. B. Son, S. N. Kim, N. Y. Kim, M.-H. Hwang, W. Lee and D. H. Lee, *Bull. Korean Chem. Soc.*, 2010, **31**, 653.
- 8 Y. Kazuta, H. Abe, T. Yamamoto, A. Matsuda and S. Shuto, *J. Org. Chem.*, 2003, **68**, 3511.
- 9 F. Romanov-Michailidis, M. Pupier, L. Guénée and A. Alexakis, *Chem. Commun.*, 2014, **50**, 13461.
- 10 K. Komine, Y. Nomura, J. Ishihara and S. Hatakeyama, *Org. Lett.*, 2015, **17**, 3918.
- 11 G. A. Molander and G. Hahn, *J. Org. Chem.*, 1986, **51**, 1135.
- 12 K. B. Sharpless, W. Amberg, Y. L. Bennani, G. A. Crispino, J. Hartung, K.-S. Jeong, H.-L. Kwong, K. Morikawa, Z.-M. Wang, D. Xu and X.-L. Zhang, *J. Org. Chem.*, 1992, **57**, 2768.
- 13 H. C. Kolb, M. S. VanNieuwenhze and K. B. Sharpless, *Chem. Rev.*, 1994, **94**, 2483.
- 14 D. Xu, G. A. Crispino and K. B. Sharpless, *J. Am. Chem. Soc.*, 1992, **114**, 7570.



- 15 H. Suemune, Y. Miyao and K. Sakai, *Chem. Pharm. Bull.*, 1989, **37**, 2523.
- 16 CCDC 2150062 contains the supplementary crystallographic data for *ent*-hypocoprins A (**1**).
- 17 I. Ohtani, T. Kusumi, Y. Kashman and H. Kakisawa, *J. Am. Chem. Soc.*, 1991, **113**, 4092.
- 18 J. A. Dale and H. S. Mosher, *J. Am. Chem. Soc.*, 1973, **95**, 512.

