Asymmetric Synthesis

Site- and Enantioselective Iridium-Catalyzed Desymmetric Mono-Hydrogenation of 1,4-Dienes

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Abstract: The control of site selectivity in asymmetric mono-hydrogenation of dienes or polyenes remains largely underdeveloped. Herein, we present a highly efficient desymmetrization of 1,4-dienes via iridium-catalyzed site- and enantioselective hydrogenation. This methodology demonstrates the first iridium-catalyzed hydrogenative desymmetrization of meso dienes and provides a concise approach to the installation of two vicinal stereogenic centers adjacent to an alkene. High isolated yields (up to 96%) and excellent diastereo- and enantioselectivities (up to 99:1 d.r. and 99% ee) were obtained for a series of divinyl carbinol and divinyl carbiniamide substrates. DFT calculations reveal that an interaction between the hydroxy oxygen and the reacting hydride is responsible for the stereoselectivity of the desymmetrization of the divinyl carbinol. Based on the calculated energy profiles, a model that simulates product distribution over time was applied to show an intuitive kinetics of this process. The usefulness of the methodology was demonstrated by the synthesis of the key intermediates of natural products zaragozic acid A and (+)-invictolide.

Introduction

Asymmetric hydrogenation of olefins has proved to be a powerful tool to produce enantiomerically enriched compounds on both laboratory and industrial scale.[1] Meanwhile, olefins are not only versatile precursors for a variety of organic transformations but also a common functional group ubiquitous in natural products, pharmaceuticals, and fine chemicals.[2] In this regard, the development of efficient methods to precisely control the site selectivity in the asymmetric mono-hydrogenation of dienes and polyenes is highly desirable for its further applications in organic synthesis (Figure 1).[3]

(a) Strategies for the site-selectivity control in asymmetric hydrogenation

Type I: Chelation controlled

Type II: Sterically controlled

Type III: Discrimination of two enantiotopic olefins (challenging)

Advantages:

- Simple achiral/meso starting material
- Allows generation of multiple chiral centers

(b) This work

Despite significant progress in the field of enantioselective hydrogenation of different types of single olefins,[2] the discrimination between different olefins in the same molecule remains a challenging task. Classically, in order to differentiate one olefin from another, a chelating group such as alcohol,[3c] carboxylic acid,[1f] or amino acid[3d] needs to be present in the vicinity of the target alkene. This strategy was often used in Rh- and Ru-catalyzed hydrogenation of functionalized olefin substrates. In recent years, Pfaltz-type iridium N,P complexes have emerged as an efficient catalytic system for asymmetric hydrogenation of minimally function-
In this case, controlling the steric difference could give equally high diastereoselectivity. Initial results are promising, as the desired product was obtained in high yields and excellent diastereomeric ratios (entries 1, 3, 6). This experimental observation was found to be in good agreement with the mathematical model developed by Schreiber et al. that illustrates the enhanced levels of ee and d.r. obtained in these cases where the starting substrate was fully converted to the mono-hydrogenated product (Table 1, entries 2–6). It was found that thiazole ligand and K$_2$CO$_3$ catalysts provided high ee and d.r. (89% NMR yield with 96:4 d.r. and 97% ee (Table 1, entry 1)).

**Table 1: Optimization of the reaction conditions**

| Entry | Cat. | P/t | Conv. [%] | 2a/2a’ [%] | d.r./ee [%] |
|-------|------|-----|-----------|------------|------------|
| 1     | A    | 3 bar/1 h | >99        | 89/11      | 96:4/97    |
| 2     | B    | 3 bar/1 h | 32         | 25/7       | 68:32/96   |
| 3     | C    | 3 bar/1 h | >99        | 64/36      | 99:1/99    |
| 4     | D    | 6 bar/1 h | 27         | 25/2       | 69:31/99   |
| 5     | E    | 6 bar/1 h | <5         | N.D.$^d$   | N.D.$^d$   |
| 6     | F    | 3 bar/1 h | >99        | 82/18      | 93:7/99    |
| 7     | A    | 3 bar/20 min | 66          | 63/3     | 94:6/95     |
| 8$^e$ | C    | 1 bar/10 min | 42         | 42/0       | 97:3/99    |
| 9     | C    | 1 bar/10 min | >99         | 95/5       | 99:1/99    |

[a] Reaction conditions: 1a (0.05 mmol), 0.5 mol% catalyst and 10 mol% K$_2$CO$_3$ in toluene (1.0 mL) at room temperature. [b] Determined by $^1$H NMR spectroscopy. [c] Enantiomeric excesses and diastereomeric ratios were determined by SFC analysis. [d] 0.2 mol% catalyst was used. [e] N.D.: not determined.

The desymmetrization of $meso$ dienes would provide a straightforward strategy in the installation of two contiguous chiral centers next to the alkene. Continuing our interest in practical regioselective asymmetric hydrogenations, we sought to develop a general hydrogenative desymmetrization of non-conjugated 1,4-diienes bearing different functionalities. Herein, we disclose a highly efficient desymmetrization of divinyl carbamols and divinyl carbamamines via iridium-catalyzed regio-, diastereomeric, and enantioselective hydrogenation. To the best of our knowledge, this method represents the first example of Ir-catalyzed hydrogenative desymmetrization of dienes. Moreover, the desymmetrization of N-containing achiral compounds via asymmetric hydrogenation is still rare.

**Figure 2.** Selected examples of natural products and bioactive compounds containing an allylic alcohol or allylic amide bearing two contiguous chiral centers adjacent to an alkene.
hydrogen for 10 minutes, where the desymmetrized product 2a was obtained in 95% NMR yield with perfect d.r. and ee.

With the optimized conditions in hand, we then examined the scope of this iridium-catalyzed desymmetric hydrogenation of divinylcarbinols (Table 2). Generally, the aromatic substrates bearing either an electron-donating or electron-withdrawing group in the para or meta position of the phenyl ring underwent the desymmetrization with excellent diastereoselectivities and enantioselectivities as well as isolated yields (2a–2g). Substrates bearing naphthyl, furyl, and thienyl moieties were also well tolerated, and the desired products (2h–2j) were obtained in high yields with excellent selectivities.

Next, divinyl carbinols with longer aliphatic sidechains in the alpha position were tested and the corresponding mono-hydrogenated products could be obtained with excellent selectivities (2k, 2l). Remarkably, the divinyl tertiary alcohols smoothly underwent the desymmetrization to afford the target products (2m–2o) in high yields with very high diastereoselectivities and enantioselectivities. This is noteworthy since the resulting tertiary chiral centers are not accessible via direct asymmetric hydrogenations, and the current strategy represents a complementary method to the classical asymmetric vinylation of ketones to prepare enantioenriched trisubstituted allylic tertiary alcohols.[13]

Finally, a series of divinyl carbinols having only aliphatic substituents were also evaluated. Overall, substrates having linear, branched, or cyclic alkyl substituents in the beta position were all applicable, good to excellent yields and high level of selectivities were obtained in these cases (2p–2t). The absolute configuration of alcohol product 2p was determined by oxidative cleavage of the olefin and comparison of the hydroxy ketone with an isoleucine derivative (see the SI for details). In addition, substrates bearing highly strained cyclopropyl (2u) and cyclobutyl (2v) underwent the desired desymmetrization smoothly without any traces of ring-opening via hydrogenolysis. Interestingly, other functionalities such as phenyl (2w), chloride (2x), and silyl ether (2y) were also compatible with the very mild hydrogenation conditions. A substrate containing cyclohexene moieties was also tested, the desired enantiomerically pure product (2z) was produced in 96% yield.

Given the success of the current desymmetrization of divinyl carbinols outlined above, we then decided to explore the desymmetric hydrogenation of divinyl carbinamine derivatives (Table 3), which are a new class of substrates for hydrogenative desymmetrization. To our delight, the Boc-protected divinyl carbinamines underwent the desired desymmetrization smoothly employing the same Ir catalyst. Notably, no base additive was required for this transformation. Both electron-withdrawing and electron-donating groups on the phenyl ring were tolerated (4a–4c). Significantly, a series of aliphatic substrates were processed to give the corresponding mono-hydrogenated products (4d–4h) in high yields and excellent diastereoselectivities and enantioselectivities. The absolute configuration of product 4d was assigned as (4S,5S) by comparing its ozonolysis product with a natural isoleucine derivative (see the SI for details).

Considering the unusually high level of ee and d.r. of the desymmetrized products as well as the very broad substrate scope that is obtained with the current method, DFT calculations were performed to investigate the stereoselectivity of the desymmetrization process. Divinyl carbinol 1a was chosen as the model substrate and catalyst ent-C was employed in the studies. Based on our previous theoretical
and experimental investigations on Ir-catalyzed asymmetric hydrogenation of olefins, a mechanism of desymmetric hydrogenation is proposed (Figure 3). The computational details and the process of searching for the most stable substrate-catalyst complex are outlined in the Supporting Information (SI).

Since the studied meso compound has two enantiotopic and two diastereotopic faces, all four individual coordination models of both the first and the second hydrogenation (Scheme 1) were tested. The calculated free energies of four different intermediates and the corresponding olefin insertion transition states of the first hydrogenation are shown in Figure 4a. The following reductive elimination steps were confirmed to have lower free energies than the olefin insertions in all cases (SI, Figure S4).

The results indicate that product 2a(1_1) will be the major product of the first hydrogenation but that significant amounts of 2a(1_3) will also form. The free energy difference between TS1(1_1) and TS1(1_3) is 1.63 kcal mol⁻¹, which suggested that over 90% diastereoselectivity could be observed in this step. Due to the much slower formation of 2a(1_2) and 2a(1_4), here we only discuss the second hydrogenation of 2a(1_1) and 2a(1_3) as shown in Figure 4b (complete reactions are shown in SI, Figure S5). We found that the activation free energy for the reaction of the minor mono-hydrogenated product 2a(1_3) via TS1(2_3) is very low, which will lead to a rapid consumption of 2a(1_3). The hydrogenation of 2a(1_1) is significantly slower and will therefore be close to the only remaining singly hydrogenated olefin after some time. All of the predictions from DFT are consistent with the experimental results. The calculated free-energy profiles reveal that the hydrogenation of 2a(1_2) and 2a(1_4) is slow due to high activation free energies for the olefin insertion. By examining the structures, it is clear that 2a(1_2) and 2a(1_4) have an unfavorable substrate–complex configuration with the olefin double bond oriented in the

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**Table 3: Scope of divinyl carbinamide.**

| Reaction conditions: | Isolated yield | Enantiomeric excess | Diastereomeric ratio |
|----------------------|----------------|---------------------|----------------------|
| Substrate (0.2 mmol), 1.0 mol % catalyst, and 10 mol % K₂CO₃ in toluene (1.0 mL) under 1–6 bar H₂ at room temperature for 10 min–1 h. | 99% ee | 97:3 d.r. | 95% ee | 97:3 d.r. | 99% ee | 99:1 d.r. | 99% ee | 99:1 d.r. | 99% ee | 99:1 d.r. | 99% ee | 99:1 d.r. |

**Scheme 1.** Hydrogenative desymmetrization process.

**Figure 3.** Proposed hydrogenation mechanism.

**Figure 4.** Free energy profile for a) the first hydrogenation; b) the second hydrogenation.
plane of the bidentate ligand (SI, Figure S3), instead of the orientation along the axial Ir–H bond in 2a(1_1) and 2a(1_3). In all favorable insertion transition states (TS1(1_1), TS1(1_3) (SI, Figure S7) and TS1(2_2), TS1(2_3) (SI, Figure S8) we found some interaction between the hydroxy oxygen atom and the reacting hydride, evidenced by O—H distances smaller than the sum of the van der Waals radii.

Using rate constants calculated using transition state theory (assuming a transmission coefficient of 1) with the calculated activation free energies, we have simulated the product distribution over time to give a more intuitive demonstration of the kinetics of the studied process.\[15\] As shown in Figure 5, in the early stage of the reaction, monohydrogenated product 2a(1_1) increases very fast and is accompanied by the generation of a small portion of 2a(1_3), which is present as a minor diastereomer in the mixture. As the hydrogenation proceeds, the amount of 2a(1_1) remains at a high level, however, the minor diastereomer or enantiomer will be selectively consumed by a kinetic resolution process in the second hydrogenation. As a result, excellent levels of ee and d.r. were obtained in the current desymmetrization process. Notably, the current model could also be applied in a generic class of reactions that proceed with a combination of enantiotopic group and diastereotopic face selectivity.

In order to demonstrate the utility of the transformation, we synthesized the side chain fragment of natural product zaragozic acid A with this desymmetrization as a key step (Scheme 2). Firstly, a gram scale hydrogenation was performed, and the desired optically pure product 2a was obtained in an undiminished yield. Then, ozonolysis of the resulting product afforded the hydroxy ketone 5, which underwent bromoform reaction and condensation to give Weinreb amide 6 in 83 % overall yield. Next, the inversion of alcohol was achieved using a Mitsunobu protocol. Finally, the PMB protection followed by alkylation furnished the target molecule 9 with 99 % ee. Compound 9 is the enantiomer of Nicolaou’s intermediate, which was initially synthesized in 12 steps with 81 % ee.\[16\]

To further illustrate the usefulness of this methodology, we continued to explore its potential in the synthesis of γ-butyrolactones (Scheme 3), which are important structural units of a wide range of pharmacologically active molecules.\[17\] Ozonolysis of the desymmetrized product of 10 followed by hydroxy-directed Wittig reaction\[18\] afforded the unsaturated ester (4S,5S)-12 as a single isomer with excellent d.r. and ee in 64 % overall yield. Surprisingly, the obtained γ-hydroxy unsaturated ester can be transformed into lactone (1'S,4R,5S)-13 directly under hydrogenation conditions with ent-C as the catalyst. We speculate that the γ-butyrolactone formation could be attributed to the acidic environment generated during the iridium-catalyzed hydrogenation.\[19\] Meanwhile, the inversion of the hydroxy group on (4S,5S)-12 using a Mitsunobu protocol provided another diastereomer of unsaturated ester (4R,5S)-12. Similarly, one-pot
hydrogenation and lactonization of (4R,5S)-12 using catalyst C led to another diastereomer of γ-butyrolactone (1’S,4S,5R)-13, which is a known intermediate in the total synthesis of natural product (+)-invictolidine.[20]

**Conclusion**

A highly efficient Ir-catalyzed site-selective desymmetric mono-hydrogenation of 1,4-diienes has been developed. This method provides a concise route to chiral allylic alcohols and allylic amides bearing two vicinal stereogenic centers adjacent to the alkene. It demonstrates the first Ir-catalyzed hydrogenation and lactonization of dienes. Impressive regio-, diastereo-, and enantioselectivities (up to 96% yield, 99:1 d.r. and 99% ee) were obtained for a broad range of divinyl carbinal (secondary and tertiary alcohols) and divinyl carbinamide substrates. DFT calculations indicate that an interaction between the hydroxy oxygen atom and active Ir-hydride is most likely responsible for the stereoselectivities. Modeling based on the calculated energy profiles was applied to give an intuitive picture of the reaction kinetics, which could be also applied for a class of desymmetrizations with enhanced diastereo- and enantioselectivities. The utility of this method was further highlighted by the synthesis of the alkyl side chain of zaragozic acid A and the formal total synthesis of (+)-invictolidine.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords:** 1,4-diene · asymmetric hydrogenation · iridium catalysis · site selectivity

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[1] For a recent book, see: a) Asymmetric Hydrogenation and Transfer Hydrogenation, (Eds.: V. Ratovelomanana-Vidal, P. Phansavath), Wiley-VCH, Weinheim, 2021; For some reviews see, b) W. S. Knowles, Angew. Chem. Int. Ed. 2002, 41, 1998–2007; Angew. Chem. 2002, 114, 2096–2107; c) R. Noyori, Angew. Chem. Int. Ed. 2002, 41, 2008–2022; Angew. Chem. 2002, 114, 2108–2123; d) D. J. Ager, A. H. M. de Vries, J. G. de Vries, Chem. Soc. Rev. 2012, 41, 3340–3380; e) C. S. Shultz, S. W. Kraska, Acc. Chem. Res. 2007, 40, 1320–1326; f) N. B. Johnson, I. C. Lennon, P. H. Moran, J. A. Ramsden, Acc. Chem. Res. 2007, 40, 1291–1299; g) P. D. Parker, X. Hou, V. M. Dong, J. Am. Chem. Soc. 2021, 143, 6724–6745.

[2] For some reviews, see: a) D. C. Silva Costa, Arab. J. Chem. 2020, 13, 799–834; b) X.-W. Lan, N.-X. Wang, X. Xing, Eur. J. Org. Chem. 2017, 5821–5851; c) H. Jiang, A. Studer, Chem. Soc. Rev. 2020, 49, 1790–1811; d) G. Yin, X. Mu, G. Liu, Acc. Chem. Res. 2016, 49, 2413–2423; e) M. Beller, J. Seayad, A. Tillack, H. Jiao, Angew. Chem. Int. Ed. 2004, 43, 3368–3398; Angew. Chem. 2004, 116, 3448–3479; f) R. I. McDonald, G. Liu, S. S. Stahl, Chem. Rev. 2011, 111, 2981–3019; g) Z. Liu, Y. Gao, T. Zeng, K. M. Engel, Isr. J. Chem. 2020, 69, 219–229.

[3] For a review on site-selective control reactions, see: a) Z. Huang, G. Dong, Acc. Chem. Res. 2017, 50, 465–471; For some selected examples of site selective reaction of dienes or polyenes, see: b) P. A. Lichtor, S. J. Miller, Nat. Chem. 2012, 4, 990–995; c) C. Desfeux, C. Bensard, C. Muzet, Org. Lett. 2020, 22, 8181–8187; For a review, see d) C. Margarita, W. Rabten, P. G. Andersson, Chem. Eur. J. 2018, 24, 8022–8028; For some selected examples of regioselective asymmetric hydrogenation, see: e) H. Takaya, T. Ohta, N. Sayo, H. Kumobayashi, S. Akutagawa, S. Inoue, I. Kasahara, R. Noyori, J. Am. Chem. Soc. 1987, 109, 1596–1597; f) D. Valentine, K. K. Johnson, W. Priester, R. C. San, K. Toth, G. Saucy, J. Org. Chem. 1980, 45, 3698–3703; g) M. J. Burk, J. G. Allen, W. F. Kiesman, J. Am. Chem. Soc. 1998, 120, 657–663; h) J. Liu, S. Krajangsri, T. Singh, G. De Seriis, N. Chunnanvej, H. Wu, P. G. Andersson, J. Am. Chem. Soc. 2017, 139, 14470–14475; i) H. Wu, C. Margarita, J. Jongcharoenkamol, M. D. Nolan, T. Singh, P. G. Andersson, Chem. Sci. 2021, 12, 1937–1943.

[4] For some reviews, see: a) T. Ayad, P. Phansavath, V. Ratovelomanana-Vidal, Chem. Rec. 2016, 16, 2754–2771; b) X. Cui, K. Burgess, Chem. Rev. 2005, 105, 3272–3296; c) W. Tang, X. Zhang, Chem. Rev. 2003, 103, 3029–3070; d) W. Zhang, Y. Chi, X. Zhang, Acc. Chem. Res. 2007, 40, 1278–1290; e) P. Etayo, A. Vidal-Ferran, Chem. Soc. Rev. 2013, 42, 728–754; f) Q.-A. Chen, Z.-S. Ye, Y. Duan, Y.-G. Zhou, Chem. Soc. Rev. 2013, 42, 497–511; g) J. I. Verendel, O. Pámies, M. Diéguez, P. G. Andersson, Chem. Rev. 2014, 114, 2130–2169; h) Z. Zhang, N. A. Butt, W. Zhang, Chem. Rev. 2016, 116, 14769–14827; i) C. S. G. Sco, R. H. Morris, Organometallics 2019, 38, 47–65.

[5] For some reviews, see: a) S.-F. Zhu, Q.-L. Zhou, Acc. Chem. Res. 2017, 50, 988–1001; b) S. J. Roseblade, A. Pfaltz, Acc. Chem. Res. 2007, 40, 1402–1411; c) C. Margarita, P. G. Andersson, J. Am. Chem. Soc. 2017, 139, 1346–1356.

[6] a) J. Merad, M. Candy, J. Pons, C. Bresy, Synthesis 2017, 49, 1938–1954; b) H. Fernández-Pérez, P. Etayo, J. R. Lao, J. L. Núñez-Rico, A. Vidal-Ferran, Chem. Commun. 2013, 49, 10666–10675.

[7] B. Nguyen, J. M. Brown, Adv. Synth. Catal. 2009, 351, 1333–1343.

[8] H. Fernández-Pérez, J. R. Lao, A. Vidal-Ferran, Organometallics, 2016, 18, 2836–2839.

[9] C. You, X. Li, Q. Gong, J. Wen, X. Zhang, J. Am. Chem. Soc. 2019, 141, 14560–14564. A number of leading examples of catalytic desymmetrization of cyclohexadienones are cited here-in.

[10] a) J. D. Bergstrom, M. M. Kurtz, D. J. Rew, A. M. Amend, J. D. Karkas, R. G. Bostedor, V. S. Bansal, C. Duforesne, F. L. Van-Middlesworth, O. D. Hensens, Proc. Natl. Acad. Sci. USA 1993, 90, 80–84; b) R. W. Burg, B. M. Miller, E. E. Baker, J. Birnbaum, S. A. Currie, R. Hartman, Y. L. Kong, R. L. Monaghan, G. Olson, I. Putter, J. B. Tuncer, H. Wallick, E. O. Stapley, R.
Oiwa, S. Omura, Antimicrob. Agents Chemother. 1979, 15, 361 – 367.

[11] a) A. Paptchikhine, K. Itto, P. G. Andersson, Chem. Commun. 2011, 47, 3989 – 3991; b) B. K. Peters, J. Liu, C. Margarita, W. Rabten, S. Kerndphon, A. Orehom, T. Morsch, P. G. Andersson, J. Am. Chem. Soc. 2016, 138, 11930 – 11935; c) J. Liu, S. Krajangsri, J. Yang, J.-Q. Li, P. G. Andersson, Nat. Catal. 2018, 1, 438 – 443; d) W. Rabten, C. Margarita, L. Eriksson, P. G. Andersson, Chem. Eur. J. 2018, 24, 1681 – 1685; e) J. Zheng, C. Margarita, S. Krajangsri, P. G. Andersson, Org. Lett. 2018, 20, 5676 – 5679; f) S. Krajangsri, H. Wu, J. Liu, W. Rabten, T. Singh, P. G. Andersson, Chem. Sci. 2019, 10, 3649 – 3653.

[12] S. L. Schreiber, T. S. Schreiber, D. B. Smith, J. Am. Chem. Soc. 1987, 109, 1525 – 1529.

[13] H. Li, P. J. Walsh, J. Am. Chem. Soc. 2005, 127, 8355 – 8361.

[14] T. L. Church, T. Rasmussen, P. G. Andersson, Organometallics 2010, 29, 6769 – 6781.

[15] We note that the reaction time is shorter than in the experiment, likely due to formation of common low energy intermediates that do not directly lead to product. Such intermediate would slow down all reaction equally. For program information, see: K. A. Johnson, Z. B. Simpson, T. Blom, Anal. Biochem. 2009, 387, 20 – 29.

[16] a) K. C. Nicolaou, E. W. Yue, Y. Naniwa, F. De Riccardis, A. Nadin, J. E. Leresche, S. La Greca, Z. Yang, Angew. Chem. Int. Ed. Engl. 1994, 33, 2184 – 2187; Angew. Chem. 1994, 106, 2306 – 2309; b) K. C. Nicolaou, E. W. Yue, S. la Greca, A. Nadin, Z. Yang, J. E. Leresche, T. Tsuri, Y. Naniwa, F. de Riccardis, Chem. Eur. J. 1995, 1, 467 – 494.

[17] a) S. Singha, E. Serrano, S. Mondal, C. G. Danillic, F. Glorius, Nat. Catal. 2020, 3, 48 – 54; b) B. Mao, M. Fañánás-Mastral, B. L. Feringa, Chem. Rev. 2017, 117, 10502 – 10566.

[18] P. Garner, S. Ramakanth, J. Org. Chem. 1987, 52, 2629 – 2631.

[19] a) R. G. Pearson, Chem. Rev. 1985, 85, 41 – 49; b) Y. Zhu, Y. Fan, K. Burgess, J. Am. Chem. Soc. 2010, 132, 6249 – 6253.

[20] a) F. E. Ziegler, W. T. Cain, A. Kneisley, E. P. Sturchak, R. T. Wester, J. Am. Chem. Soc. 1988, 110, 5442 – 5452; b) T. Honda, S.-i. Yamane, F. Ishikawa, M. Katoh, Tetrahedron 1996, 52, 12177 – 12184.