



Construction of highly enantioenriched spirocyclopentaneoxindoles containing four consecutive stereocenters via thiourea-catalyzed asymmetric Michael–Henry cascade reactions

Yonglei Du¹, Jian Li², Kerong Chen², Chenglin Wu², Yu Zhou^{*2} and Hong Liu^{*2,3}

Full Research Paper

Open Access

Address:

¹Nano Science and Technology Institute, University of Science and Technology of China, 166 Ren Ai Road, Suzhou 215123, China, ²CAS Key Laboratory of Receptor Research, Shanghai Institute of Materia Medica, Chinese Academy of Sciences, 555, Zu Chong Zhi Road, Shanghai 201203, China and ³University of Chinese Academy of Sciences, NO.19A Yuquan Road, Beijing 100049, China

Email:

Yu Zhou^{*} - zhouyu@simm.ac.cn; Hong Liu^{*} - hliu@simm.ac.cn

* Corresponding author

Keywords:

asymmetric synthesis; four consecutive stereocenters; Michael–Henry cascade reactions; spirocyclopentaneoxindoles; thioureas

Beilstein J. Org. Chem. **2017**, *13*, 1342–1349.
doi:10.3762/bjoc.13.131

Received: 17 March 2017
Accepted: 21 June 2017
Published: 07 July 2017

Associate Editor: T. P. Yoon

© 2017 Du et al.; licensee Beilstein-Institut.
License and terms: see end of document.

Abstract

The thiourea-catalyzed asymmetric synthesis of highly enantioenriched spirocyclopentaneoxindoles containing chiral amide functional groups using simple 3-substituted oxindoles and nitrovinylacetamide as starting materials was achieved successfully. This protocol features operational simplicity, high atom economy, and high catalytic asymmetry, thus representing a versatile approach to the synthesis of highly enantioenriched spirocyclopentaneoxindoles.

Introduction

The spirocyclic oxindole core represents an important scaffold that is encountered frequently in many biologically active molecules and natural products (Figure 1) [1-19]. Despite many advances in asymmetric synthesis in the construction of heterocyclic spirooxindoles in the past decade [2,4,11,20-22], the development of general and practical strategies to obtain saturated spirocyclopentaneoxindoles containing multiple

contiguous stereocenters remains challenging [23-26]. The medicinal properties of these frameworks mean that fast enrichment of spirooxindoles bearing diverse functional groups is of considerable importance.

Recently, an increasing number of asymmetric catalysis strategies with chiral transition metals [27-33], organocatalysts such

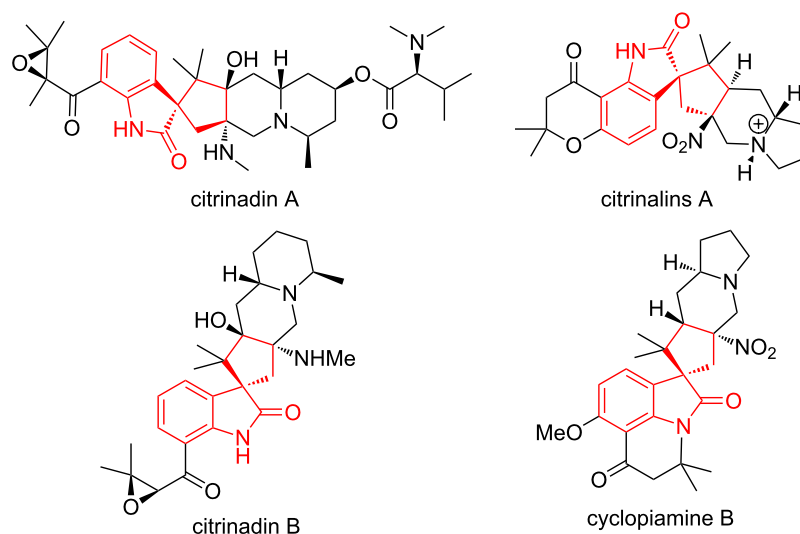


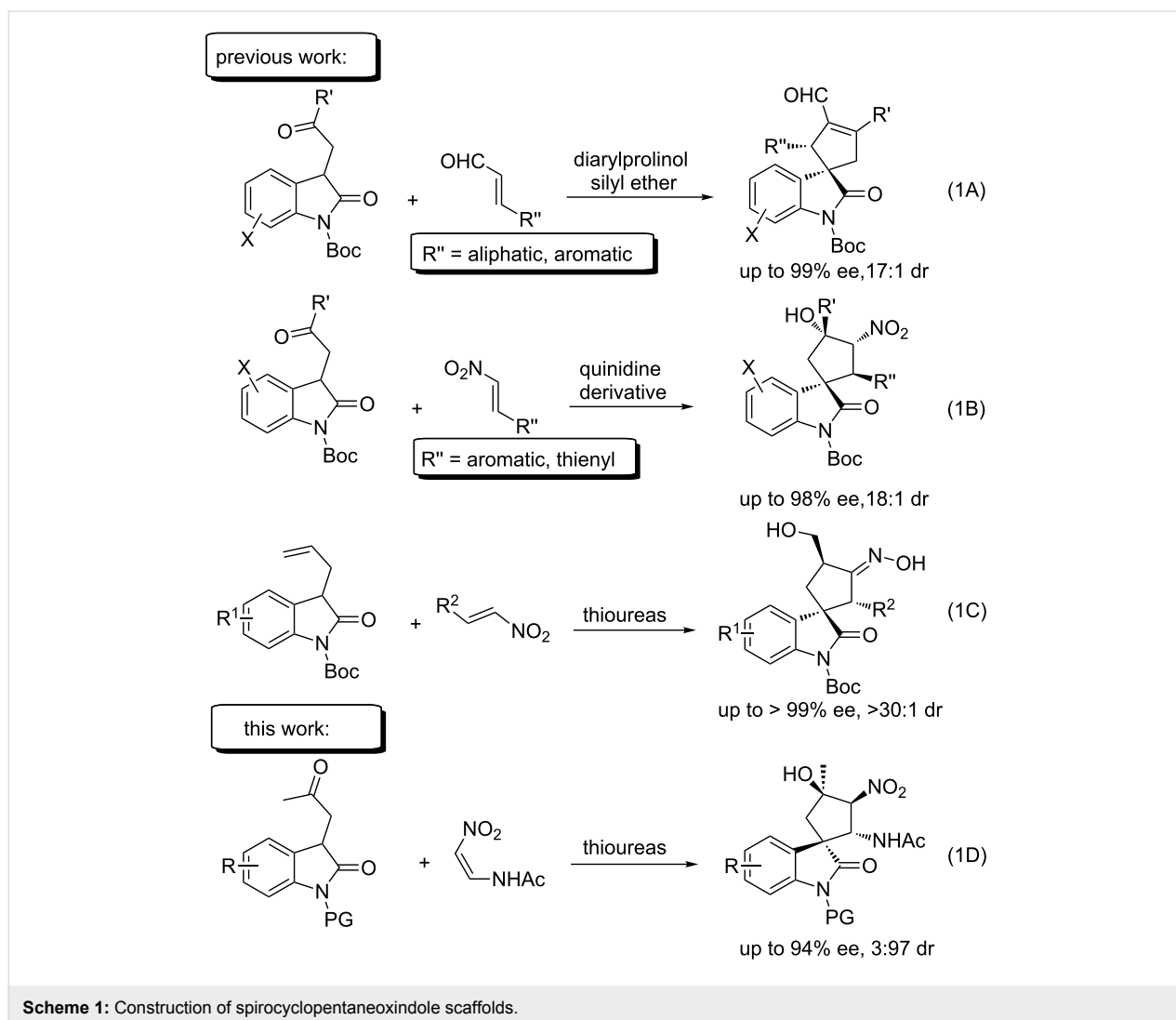
Figure 1: Representative spirooxindole natural products.

as secondary amines [34–36], nucleophilic phosphines [26,37–44], tertiary amines [45], *N*-heterocyclic carbenes (NHCs) [46–48], and cinchona alkaloid derivatives [25,28,49,50] have been used to construct successfully spirooxindole privileged scaffolds. However, most of them were devoted to exploring new catalyst systems to improve the reaction efficiency and selectivity [51–64], and studies extending the reaction scope using functionalized nitrovinylacetamides are rare. Chiral thioureas [28,38,39] have evolved as powerful hydrogen bonding catalysts for the asymmetric synthesis of spirocyclopentaneoxindoles, which have been demonstrated as acceptable but still considerably limited. Organocatalytic iminium–enamine cascade reactions [35] (Scheme 1, reaction 1A) and Michael–Henry cascade reactions [25] (Scheme 1, reaction 1B) reported by Barbas III's group involve the cyclization between α,β -unsaturated aldehydes and nitrostyrenes with 3-substituted oxindoles to generate the corresponding CHO- or NO₂-substituted spirooxindole derivatives with good enantiomeric excess (ee) values, respectively. However, the utility of the reaction is limited to α,β -unsaturated aldehydes with aromatic/alkane substitutions and nitroolefins with aromatic substitutions. Additionally, Shao's group (Scheme 1, reaction 1C) developed a one-pot thiourea-catalyzed Michael addition/intramolecular silyl nitronate-olefin cycloaddition (ISOC)/fragmentation sequence to produce highly enantioenriched spirocyclopentaneoxindoles containing an oxime functional group from easily accessible 3-allyl-substituted oxindoles and nitroolefins, which has received wide attention because of its high efficiency in constructing functionalized spirocyclopentaneoxindoles. However, lower temperatures are required (–30 °C) [50]. Therefore, it is highly desirable to develop novel and efficient methods to access directly various spirocycles. In our continuous endeavor

to develop effective strategies to construct biologically active spirocyclic oxindoles [65–68], we have built successfully interesting spirooxindoles via an NHC-catalyzed [4 + 2] annulation involving an oxidative γ -carbon activation of common α,β -unsaturated aldehydes [68]. Herein, we report another effective asymmetric catalytic synthesis of saturated spirocyclopentaneoxindoles containing four consecutive stereocenters with 3-substituted oxindoles and nitrovinylacetamide using a bifunctional thiourea catalyst in good yields (up to 95%) with excellent diastereoselectivity (up to 3:97) and enantioselectivity (up to 94%) (Scheme 1, reaction 1D).

Results and Discussion

To establish the optimal experimental conditions for the synthesis of spirocyclopentaneoxindoles, we chose 3-substituted oxindole **1a** and nitrovinylacetamide (**2a**) as the model substrates, and the results are summarized in Table 1. Initially, a variety of organocatalysts (**a–f**) were investigated in CH₂Cl₂ at –20 °C for 12 h to evaluate their ability to promote the transformation (Table 1, entries 1–6). When cinchona alkaloid-derived catalyst **a** and quinine-derived amine catalyst **b** were tested, however, poor yields or ee values were obtained, respectively (Table 1, entries 1 and 2). Further experiments showed that a bifunctional thiourea catalyst **d** was the most efficient for the synthesis of spirocyclic oxindole derivatives in good yields (80%) with excellent diastereoselectivity (8:92 dr), and moderate enantioselectivity (83% ee, Table 1, entries 3–6). Therefore, catalyst **d** was chosen as the optimal catalyst for further investigation (Table 1, entry 4). The reaction temperature was investigated, however elevated temperatures are detrimental (Table 1, entries 4, 12, 13). Different solvents, such as methanol, toluene, acetone, ether and chloroform were further screened. The results



Scheme 1: Construction of spirocyclopentaneoxindole scaffolds.

suggested that changing the solvent had an adverse effect on the ee value, and CH_2Cl_2 remained the best choice for this transformation (Table 1, entries 4, 7–11). Subsequently, we investigated some additives, for example, *p*- $\text{MeC}_6\text{H}_4\text{SO}_3\text{H}$, trimethylsilyl chloride (TMSCl) and trifluoroacetic acid (TFA) for this catalytic system to increase the ee value of the target product; however, the use of the additives proved ineffective (Table 1, entries 15–17).

With the optimized reaction conditions established, we next investigated the substrate scope of 3-substituted oxindoles in this transformation with nitroolefins (Scheme 2). In general, the diverse 3-substituted oxindoles **1a–j** with electron-donating, electron-withdrawing, or halide groups could undergo a smooth reaction with nitrovinylacetamide (**2a**) in moderate yields, good diastereoselectivity, and general enantioselectivity (**3a–j**). For example, the protocol showed moderate yields (75–76%), excellent diastereoselectivity (9:91–3:97 dr) and good enantio-

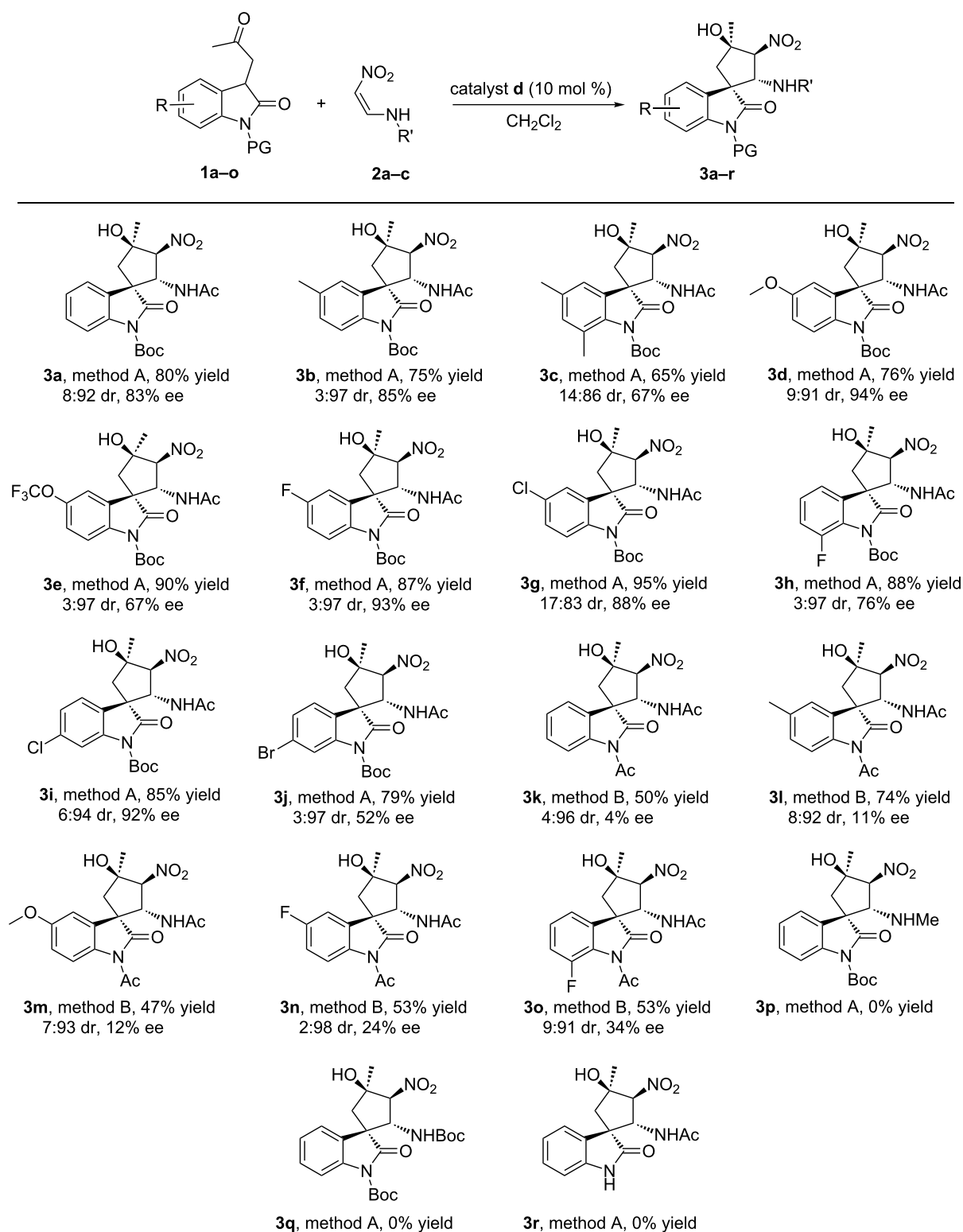
selectivity (85–94% ee) for substrates containing 5- CH_3 or 5- OCH_3 groups (**3b** and **3d**). Substrates carrying 5-F, 7-F, 5-Cl and 6-Cl afforded the corresponding products **3f–i** in high yields (85–95%) with excellent diastereoselectivity (17:83–3:97 dr) and good enantioselectivity (76–93% ee). Surprisingly, introducing a bromo group into 6-position of the oxindole scaffold resulted in a low enantioselectivity (52% ee for **3j**), although at a high yield (79%) and excellent diastereoselectivity (3:97 dr). To further extend the reaction scope, we attempted to exchange the *N*-Boc group of the 3-substituted oxindoles with other protecting groups, such as Bn, CH_3 or an acetyl group. The results demonstrated that only an acetyl protecting group proved to be well tolerated, providing for the efficient synthesis of spirocyclopentaneoxindoles **3k–o** with moderate yields (47–74%) and excellent diastereoselectivity (9:91–2:98 dr). However, replacing the *N*-Boc group with an *N*-acetyl group on spirooxindoles had a negative effect on the stereoselectivities of the target products, probably because the *N*-acetyl group

Table 1: Optimization for the reaction conditions^a.

entry	catalyst	solvent	additive	yield(%) ^b	dr ^c	ee (%) ^d
1	a	CH ₂ Cl ₂	–	37	5:95	99
2	b	CH ₂ Cl ₂	–	57	20:80	10
3	c	CH ₂ Cl ₂	–	6	16:84	6
4	d	CH₂Cl₂	–	80	8:92	83
5	e	CH ₂ Cl ₂	–	21	4:96	29
6	f	CH ₂ Cl ₂	–	40	–	–
7	d	CH ₃ OH	–	–	–	16
8	d	toluene	–	–	–	47
9	d	acetone	–	–	–	28
10	d	Et ₂ O	–	–	–	41
11	d	CHCl ₃	–	–	–	2
12 ^e	d	CH ₂ Cl ₂	–	56	–	4
13 ^f	d	CH ₂ Cl ₂	–	trace	–	–
14 ^g	d	CH ₂ Cl ₂	–	72	–	82
15 ^h	d	CH ₂ Cl ₂	<i>p</i> -MeC ₆ H ₄ SO ₃ H	–	–	25
16 ^h	d	CH ₂ Cl ₂	TMSCl	–	–	13
17 ^h	d	CH ₂ Cl ₂	TFA	–	–	11

^aReaction conditions: Unless noted, the reaction was carried out with **1a** (0.11 mmol), **2a** (0.1 mmol), catalyst **a–f** (0.01 mmol), solvent (2–3 mL), 12 h.^bIsolated yield. ^cDetermined by ¹H NMR spectroscopy of the crude mixture. ^dDetermined by chiral HPLC analysis of the major diastereomer.^eTemperature (0 °C). ^fTemperature (rt). ^gSolvent (1 mL). ^h*p*-MeC₆H₄SO₃H (0.01 mmol), TMSCl (0.01 mmol), TFA (0.01 mmol) as the additive.

“–” represents: not determined.



Scheme 2: Scope of enantioselective synthesis of spirooxindoles. Reaction conditions: catalyst **d** (0.01 mmol), oxindoles **1a-o** (0.11 mmol) and nitroolefins **2a-c** (0.1 mmol) in CH_2Cl_2 (3 mL), method A or method B. The ee values were determined by chiral HPLC analysis of major diastereomer. The dr values were determined by ^1H NMR analysis. Method A: with 10 mol % of **d** as a catalyst, -20°C , 12 h. Method B: with 10 mol % of **d** as a catalyst, -10°C , 24 h.

decreases steric hindrance. In addition, substituents (CH₃, Boc) at R' and the free N-H substituted oxindole were investigated that did not give the corresponding target products (**3p**, **3q** and **3r**).

On the basis of the dual activation model proposed by Takemoto et al. [69], a plausible reaction mechanism was proposed in Scheme 3. The multifunctional organocatalyst **d** has a chiral scaffold including a thiourea moiety and an amino group. Both the 3-substituted oxindoles **1** and nitrovinylacetamide (**2a**) that participate in this reaction are activated simultaneously via multiple hydrogen bonds. In addition, the electrophilicity of the reacting carbon center of nitrovinylacetamide is likely enhanced by H-bonding, thereby enabling the Michael addition to construct a unique quaternary stereogenic center complex **A** which would cyclize concurrently via Henry reaction to give the product **3** and regenerates the catalyst **d**. The absolute configuration of **3g** was determined by X-ray analysis (see Supporting Information File 1, Figure S1).

Conclusion

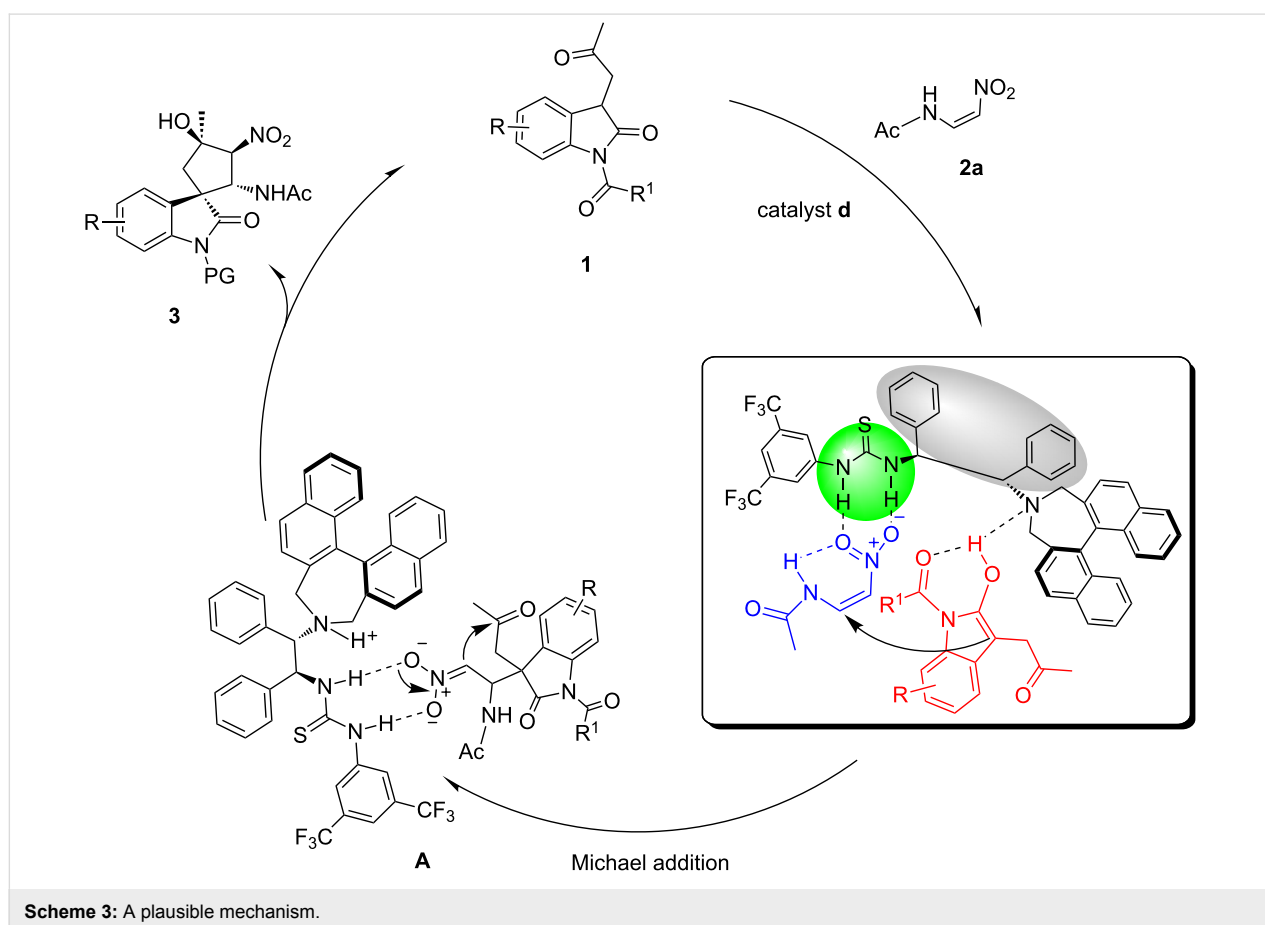
We have developed a highly efficient and practical strategy for a single step construction of saturated spirocyclopentaneoxin-

doles containing four consecutive stereocenters and a unique quaternary stereogenic center, with good yields, and excellent diastereoselectivity and enantioselectivity using thiourea-catalyzed Michael–Henry cascade reactions. We anticipate that this reaction will simplify the synthesis of complex spirooxindoles containing multiple chiral centers with potential pharmacological properties.

Experimental

General procedure for the synthesis of products (3a–j): To a mixture of **1a–j** (0.11 mmol) and **2a** (0.1 mmol) in CH₂Cl₂ (3 mL) was added catalyst **d** (0.01 mmol). Then the mixture was stirred at –20 °C for 12 h. After completion of the reaction, the solvent was removed by evaporation. The crude product was purified by column chromatography on silica gel to afford the desired products **3a–j**.

General procedure for the synthesis of products (3k–o): 3-Substituted oxindoles **1k–o** (0.11 mmol) and nitrovinylacetamide (**2a**, 0.1 mmol) were dissolved in 3 mL CH₂Cl₂, the catalyst **d** (0.01 mmol) was added at –10 °C for 24 h. After nitrovinylacetamide (**2a**) was consumed completely, the solvent was removed under vacuum. The crude product was puri-



Scheme 3: A plausible mechanism.

fied by column chromatography on silica gel to afford the desired products **3k–o**.

Supporting Information

Supporting Information File 1

General information, experimental details, characterization data and copies of ^1H and ^{13}C NMR spectra, and HPLC experimental data.

[<http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-13-131-S1.pdf>]

Acknowledgements

We gratefully acknowledge financial support from the National Natural Science Foundation of China (81620108027, 21632008, 91229204 and 81220108025) the Major Project of Chinese National Programs for Fundamental Research and Development (2015CB910304), and National S&T Major Projects (2014ZX09507002-001).

References

- Sharma, N.; Li, Z.; Sharma, U. K.; Van der Eycken, E. V. *Org. Lett.* **2014**, *16*, 3884–3887. doi:10.1021/ol5019079
- Ball-Jones, N. R.; Badillo, J. J.; Franz, A. K. *Org. Biomol. Chem.* **2012**, *10*, 5165–5181. doi:10.1039/C2OB25184A
- Yu, J.; Shi, F.; Gong, L.-Z. *Acc. Chem. Res.* **2011**, *44*, 1156–1171. doi:10.1021/ar2000343
- Zhou, F.; Liu, Y.-L.; Zhou, J. *Adv. Synth. Catal.* **2010**, *352*, 1381–1407. doi:10.1002/adsc.201000161
- Rottmann, M.; McNamara, C.; Yeung, B. K. S.; Lee, M. C. S.; Zou, B.; Russell, B.; Seitz, P.; Plouffe, D. M.; Dharia, N. V.; Tan, J.; Cohen, S. B.; Spencer, K. R.; González-Paez, G. E.; Lakshminarayana, S. B.; Goh, A.; Suwanarusk, R.; Jegla, T.; Schmitt, E. K.; Beck, H.-P.; Brun, R.; Nosten, F.; Renia, L.; Dartois, V.; Keller, T. H.; Fidock, D. A.; Winzeler, E. A.; Diagona, T. T. *Science* **2010**, *329*, 1175–1180. doi:10.1126/science.1193225
- Antonchick, A. P.; Gerding-Reimers, C.; Catarinella, M.; Schuermann, M.; Preut, H.; Ziegler, S.; Rauh, D.; Waldmann, H. *Nat. Chem.* **2010**, *2*, 735–740. doi:10.1038/nchem.730
- Shangary, S.; Qin, D.; McEachern, D.; Liu, M.; Miller, R. S.; Qiu, S.; Nikolovska-Coleska, Z.; Ding, K.; Wang, G.; Chen, J.; Bernard, D.; Zhang, J.; Lu, Y.; Gu, Q.; Shah, R. B.; Pienta, K. J.; Ling, X.; Kang, S.; Guo, M.; Sun, Y.; Yang, D.; Wang, S. *Proc. Natl. Acad. Sci. U. S. A.* **2008**, *105*, 3933–3938. doi:10.1073/pnas.0708917105
- Periyasami, G.; Raghunathan, R.; Surendiran, G.; Mathivanan, N. *Bioorg. Med. Chem. Lett.* **2008**, *18*, 2342–2345. doi:10.1016/j.bmcl.2008.02.065
- Mohr, J. T.; Krout, M. R.; Stoltz, B. M. *Nature* **2008**, *455*, 323–332. doi:10.1038/nature07370
- Fensome, A.; Adams, W. R.; Adams, A. L.; Berrodin, T. J.; Cohen, J.; Huselton, C.; Illenberger, A.; Kern, J. C.; Hudak, V. A.; Marella, M. A.; Melenski, E. G.; McComas, C. C.; Mugford, C. A.; Slayden, O. D.; Yudit, M.; Zhang, Z.; Zhang, P.; Zhu, Y.; Winneker, R. C.; Wrobel, J. E. *J. Med. Chem.* **2008**, *51*, 1861–1873. doi:10.1021/jm701080t
- Galliford, C. V.; Scheidt, K. A. *Angew. Chem., Int. Ed.* **2007**, *46*, 8748–8758. doi:10.1002/anie.200701342
- Marti, C.; Carreira, E. M. *Eur. J. Org. Chem.* **2003**, 2209–2219. doi:10.1002/ejoc.200300050
- Mercado-Marin, E. V.; Garcia-Reynaga, P.; Romminger, S.; Pimenta, E. F.; Romney, D. K.; Lodewyk, M. W.; Williams, D. E.; Andersen, R. J.; Miller, S. J.; Tantillo, D. J.; Berlinck, R. G. S.; Sarpong, R. *Nature* **2014**, *509*, 318–324. doi:10.1038/nature13273
- Pimenta, E. F.; Vita-Marques, A. M.; Tininis, A.; Seleglim, M. H. R.; Sette, L. D.; Veloso, K.; Ferreira, A. G.; Williams, D. E.; Patrick, B. O.; Dalisay, D. S.; Andersen, R. J.; Berlinck, R. G. S. *J. Nat. Prod.* **2010**, *73*, 1821–1832. doi:10.1021/np100470h
- McIver, A. L.; Deiters, A. *Org. Lett.* **2010**, *12*, 1288–1291. doi:10.1021/ol100177u
- Trost, B. M.; Brennan, M. K. *Synthesis* **2009**, 3003–3025. doi:10.1055/s-0029-1216975
- Greshock, T. J.; Grubbs, A. W.; Jiao, P.; Wicklow, D. T.; Gloer, J. B.; Williams, R. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 3573–3577. doi:10.1002/anie.200800106
- Mugishima, T.; Tsuda, M.; Kasai, Y.; Ishiyama, H.; Fukushi, E.; Kawabata, J.; Watanabe, M.; Akao, K.; Kobayashi, J. *J. Org. Chem.* **2005**, *70*, 9430–9435. doi:10.1021/jo0514990
- Bond, R. F.; Boeyens, J. C. A.; Holzapfel, C. W.; Steyn, P. S. *J. Chem. Soc., Perkin Trans. 1* **1979**, 1751–1761. doi:10.1039/p19790001751
- Hong, L.; Wang, R. *Adv. Synth. Catal.* **2013**, *355*, 1023–1052. doi:10.1002/adsc.201200808
- Singh, G. S.; Desta, Z. Y. *Chem. Rev.* **2012**, *112*, 6104–6155. doi:10.1021/cr300135y
- Cheng, D.; Ishihara, Y.; Tan, B.; Barbas, C. F., III. *ACS Catal.* **2014**, *4*, 743–762. doi:10.1021/cs401172r
- Zhou, B.; Yang, Y.; Shi, J.; Luo, Z.; Li, Y. *J. Org. Chem.* **2013**, *78*, 2897–2907. doi:10.1021/jo302655u
- Shi, Y.; Lin, A.; Mao, H.; Mao, Z.; Li, W.; Hu, H.; Zhu, C.; Cheng, Y. *Chem. – Eur. J.* **2013**, *19*, 1914–1918. doi:10.1002/chem.201202937
- Albertshofer, K.; Tan, B.; Barbas, C. F., III. *Org. Lett.* **2012**, *14*, 1834–1837. doi:10.1021/ol300441z
- Tan, B.; Candeias, N. R.; Barbas, C. F., III. *J. Am. Chem. Soc.* **2011**, *133*, 4672–4675. doi:10.1021/ja110147w
- Sun, W.; Zhu, G.; Wu, C.; Hong, L.; Wang, R. *Chem. – Eur. J.* **2012**, *18*, 13959–13963. doi:10.1002/chem.201201976
- Li, Y.-M.; Li, X.; Peng, F.-Z.; Li, Z.-Q.; Wu, S.-T.; Sun, Z.-W.; Zhang, H.-B.; Shao, Z.-H. *Org. Lett.* **2011**, *13*, 6200–6203. doi:10.1021/ol202624f
- Trost, B. M.; Cramer, N.; Silverman, S. M. *J. Am. Chem. Soc.* **2007**, *129*, 12396–12397. doi:10.1021/ja075335w
- Corkey, B. K.; Toste, F. D. *J. Am. Chem. Soc.* **2007**, *129*, 2764–2765. doi:10.1021/ja068723r
- Parthasarathy, K.; Praveen, C.; Jeyaveeran, J. C.; Prince, A. A. M. *Bioorg. Med. Chem. Lett.* **2016**, *26*, 4310–4317. doi:10.1016/j.bmcl.2016.07.036
- Arai, T.; Miyazaki, T.; Ogawa, H.; Masu, H. *Org. Lett.* **2016**, *18*, 5824–5827. doi:10.1021/acs.orglett.6b02783
- Dhara, K.; Mandal, T.; Das, J.; Dash, J. *Angew. Chem., Int. Ed.* **2015**, *54*, 15831–15835. doi:10.1002/anie.201508746
- Ding, L.-Z.; Zhong, T.-S.; Wu, H.; Wang, Y.-M. *Eur. J. Org. Chem.* **2014**, 5139–5143. doi:10.1002/ejoc.201402687
- Albertshofer, K.; Anderson, K. E.; Barbas, C. F., III. *Org. Lett.* **2012**, *14*, 5968–5971. doi:10.1021/ol302876c

36. Zhang, S. L.; Xie, H.-X.; Zhu, J.; Li, H.; Zhang, X.-S.; Li, J.; Wang, W. *Nat. Commun.* **2011**, *2*, 211. doi:10.1038/ncomms1214
37. Wang, Y.; Liu, L.; Zhang, T.; Zhong, N.-J.; Wang, D.; Chen, Y.-J. *J. Org. Chem.* **2012**, *77*, 4143–4147. doi:10.1021/jo3002535
38. Doyle, A. G.; Jacobsen, E. N. *Chem. Rev.* **2007**, *107*, 5713–5743. doi:10.1021/cr068373r
39. Zhong, F.; Han, X.; Wang, Y.; Lu, Y. *Angew. Chem., Int. Ed.* **2011**, *50*, 7837–7841. doi:10.1002/anie.201102094
40. Voituriez, A.; Pinto, N.; Neel, M.; Retailleau, P.; Marinetti, A. *Chem. – Eur. J.* **2010**, *16*, 12541–12544. doi:10.1002/chem.201001791
41. Pinto, N.; Neel, M.; Panossian, A.; Retailleau, P.; Frison, G.; Voituriez, A.; Marinetti, A. *Chem. – Eur. J.* **2010**, *16*, 1033–1045. doi:10.1002/chem.200901893
42. Zhang, J.; Cao, D.; Wang, H.; Zheng, C.; Zhao, G.; Shang, Y. *J. Org. Chem.* **2016**, *81*, 10558–10568. doi:10.1021/acs.joc.6b01553
43. Zhang, X.-Y.; Shen, Z.; Hu, L.-L.; Wang, L.-J.; Lin, Y.-S.; Xie, J.-W.; Cui, H.-L. *Tetrahedron Lett.* **2016**, *57*, 3790–3794. doi:10.1016/j.tetlet.2016.07.035
44. Voituriez, A.; Marinetti, A.; Gicquel, M. *Synlett* **2015**, *26*, 142–166. doi:10.1055/s-0034-1379251
45. Peng, J.; Huang, X.; Jiang, L.; Cui, H.-L.; Chen, Y.-C. *Org. Lett.* **2011**, *13*, 4584–4587. doi:10.1021/ol201776h
46. Jiang, K.; Tiwari, B.; Chi, Y. R. *Org. Lett.* **2012**, *14*, 2382–2385. doi:10.1021/ol3008028
47. Grossmann, A.; Enders, D. *Angew. Chem., Int. Ed.* **2012**, *51*, 314–325. doi:10.1002/anie.201105415
48. Menon, R. S.; Biju, A. T.; Nair, V. *Chem. Soc. Rev.* **2015**, *44*, 5040–5052. doi:10.1039/c5cs00162e
49. Tan, B.; Candeias, N. R.; Barbas, C. F., III. *Nat. Chem.* **2011**, *3*, 473–477. doi:10.1038/nchem.1039
50. Li, X.; Li, Y.-M.; Peng, F.-Z.; Wu, S.-T.; Li, Z.-Q.; Sun, Z.-W.; Zhang, H.-B.; Shao, Z.-H. *Org. Lett.* **2011**, *13*, 6160–6163. doi:10.1021/ol2024955
51. Zhu, S.; Yu, S.; Ma, D. *Angew. Chem., Int. Ed.* **2008**, *47*, 545–548. doi:10.1002/anie.200704161
52. Wiesner, M.; Revell, J. D.; Wennemers, H. *Angew. Chem., Int. Ed.* **2008**, *47*, 1871–1874. doi:10.1002/anie.200704972
53. Wiesner, M.; Revell, J. D.; Tonazzi, S.; Wennemers, H. *J. Am. Chem. Soc.* **2008**, *130*, 5610–5611. doi:10.1021/ja801027s
54. Hayashi, Y.; Itoh, T.; Ohkubo, M.; Ishikawa, H. *Angew. Chem., Int. Ed.* **2008**, *47*, 4722–4724. doi:10.1002/anie.200801130
55. García-García, P.; Ladépêche, A.; Halder, R.; List, B. *Angew. Chem., Int. Ed.* **2008**, *47*, 4719–4721. doi:10.1002/anie.200800847
56. McCooley, S. H.; Connon, S. J. *Org. Lett.* **2007**, *9*, 599–602. doi:10.1021/ol0628006
57. Xu, Y.; Zou, W.; Sundén, H.; Ibrahem, S.; Córdova, A. *Adv. Synth. Catal.* **2006**, *348*, 418–424. doi:10.1002/adsc.200505373
58. Wang, J.; Li, H.; Lou, B.; Zu, L.; Guo, H.; Wang, W. *Chem. – Eur. J.* **2006**, *12*, 4321–4332. doi:10.1002/chem.200600115
59. Palomo, C.; Vera, S.; Mielgo, A.; Gómez-Bengoa, E. *Angew. Chem., Int. Ed.* **2006**, *45*, 5984–5987. doi:10.1002/anie.200602207
60. Mossé, S.; Alexakis, A. *Org. Lett.* **2006**, *8*, 3577–3580. doi:10.1021/ol0614727
61. Luo, S.; Mi, X.; Zhang, L.; Liu, S.; Xu, H.; Cheng, J.-P. *Angew. Chem., Int. Ed.* **2006**, *45*, 3093–3097. doi:10.1002/anie.200600048
62. Wang, W.; Wang, J.; Li, H. *Angew. Chem., Int. Ed.* **2005**, *44*, 1369–1371. doi:10.1002/anie.200461959
63. Hayashi, Y.; Gotoh, H.; Hayashi, T.; Shoji, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 4212–4215. doi:10.1002/anie.200500599
64. Andrey, O.; Alexakis, A.; Tomassini, A.; Bernardinelli, G. *Adv. Synth. Catal.* **2004**, *346*, 1147–1168. doi:10.1002/adsc.200404037
65. Cai, H.; Zhou, Y.; Zhang, D.; Xu, J.; Liu, H. *Chem. Commun.* **2014**, *50*, 14771–14774. doi:10.1039/c4cc06000h
66. Rong, X.; Yao, H.; Xia, W.; Du, Y.; Zhou, Y.; Liu, H. *ACS Comb. Sci.* **2016**, *18*, 220–224. doi:10.1021/acscmbosci.5b00197
67. Chen, X.; Chen, H.; Ji, X.; Jiang, H.; Yao, Z.-J.; Liu, H. *Org. Lett.* **2013**, *15*, 1846–1849. doi:10.1021/ol4004542
68. Yao, H.; Zhou, Y.; Chen, X.; Zhang, P.; Xu, J.; Liu, H. *J. Org. Chem.* **2016**, *81*, 8888–8899. doi:10.1021/acs.joc.6b01596
69. Okino, T.; Hoashi, Y.; Furukawa, T.; Xu, X.; Takemoto, Y. *J. Am. Chem. Soc.* **2005**, *127*, 119–125. doi:10.1021/ja044370p

License and Terms

This is an Open Access article under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The license is subject to the *Beilstein Journal of Organic Chemistry* terms and conditions: (<http://www.beilstein-journals.org/bjoc>)

The definitive version of this article is the electronic one which can be found at: [doi:10.3762/bjoc.13.131](https://doi.org/10.3762/bjoc.13.131)