Relay Catalysis

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Bimetallic Gold(I)/Chiral *N,N′*-Dioxide Nickel(II) Asymmetric Relay Catalysis: Chemo- and Enantioselective Synthesis of Spiroketals and Spiroaminals

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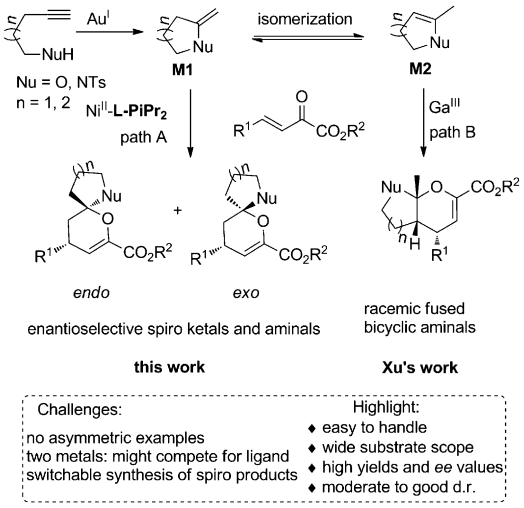
Abstract: *A highly efficient asymmetric cascade reaction between keto esters and alkynyl alcohols and amides is reported. The success of the reaction was attributed to the combination of chiral Lewis acid N,N′-dioxide nickel(II) catalysis with achiral π-acid gold(I) catalysis working as an asymmetric relay catalytic system. The corresponding spiroketals and spiroaminals were synthesized in up to 99% yield, 19:1 d.r., and more than 99% ee under mild reaction conditions. Control experiments suggest that the N,N′-dioxide ligand was essential for the formation of the spiro products.*

Over the past decade, organo/metal and metal/metal combined dual catalyses have received a tremendous amount of attention as they can promote transformations that are not accessible through individual catalytic systems.[1] To date, remarkable progress has been made on organo/metal combined catalysis in the field of asymmetric synthesis.[2] Initiated by independent work by Gong et al. and Takemoto and co-workers in 2001,[3] versatile organo/metal dual catalysis systems, such as chiral phosphoric acids/Au,[4] aminocatalysts/metal,[5] quinine-based bifunctional molecules/Ag,[6] N-heterocyclic carbene catalysts/metal,[7] and others,[8] have been developed. For metal/metal combined catalysis, Toste and Corkey discovered a chiral bisphosphine Pd^{II}/Yb^{III} dual catalyst system for the enantioselective intramolecular Conia-ene reaction in 2005.[9a] In 2010, Hu and co-workers reported a cooperative catalytic system containing $[Rh_2(OAc)_4]$ and (*S*)-*t*Bu-box-$Zn(OTf)_2$ for an enantioselective three-component reaction of diazo compounds with water and α,β-unsaturated 2-acyl imidazoles.[9b] However, the combination of two metal catalysts for asymmetric reactions was still limited.[9] One of the perceived challenges is that the ligand must be compatible with two distinct metal centers. Thus, the development of new chiral dual catalysis systems employing dual-metal catalysts for asymmetric synthesis is both important and desirable.

Alkynyl alcohols and amides are versatile precursors which can undergo intramolecular cyclization to form intermediate **M1** in the presence of gold(I) (Scheme 1).[10] If the resulting electron-rich alkene **M1**, acting as a dienophile precursor, reacted directly with keto esters, the inverse-electron-demand hetero-Diels–Alder (IED hetero-DA) reaction can occur and spiroketals and aminals can be obtained (Scheme 1, path A). The reaction is important because the spiroketals and aminals, in particular [6,5] congeners, are key structural units of a variety of natural products.[11] However, intermediate **M1** can readily isomerize into **M2**,[12,13a] which is more stable, and fused bicyclo products were usually obtained. For example, Xu et al. demonstrated that the combination of π-acid gold(I) catalysis with σ-metal Lewis acid Ga^{III} catalysis could be used to directly convert the alkynyl amides into racemic fused bicyclo aminals by a bimetallic relay catalytic strategy (path B).[13] We conceived that when a bulkier chiral ligand was incorporated, the less sterically hindered enamide **M1** would more reactive than **M2** in the IED hetero-DA reaction, and the isomerization equilibrium would move from **M2** to **M1**. Using this method, the useful spiroketals and aminals could be exclusively and enantioselectively obtained rather than the fused isomers. To our knowledge, no catalytic system to trap intermediate **M1** through path A has been developed to date. Herein, we report our efforts to develop a bimetallic gold(I)/chiral *N,N′*-dioxide nickel(II) complex[14] catalytic



Scheme 1. Lewis acids catalysis combined with π-acid gold(I) catalysis (path A) compared to previous work by Xu and co-workers (path B; Ref. [13]). See Table 1 for the structure of **L-PiPr$_2$**.

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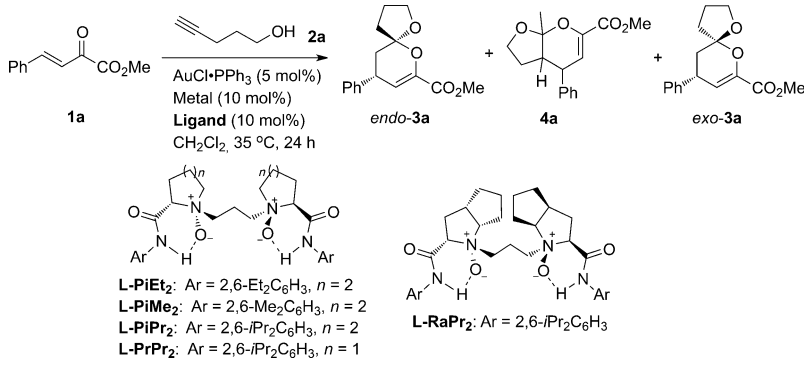
system to control the cascade reaction of keto esters with alkynyl alcohols and amides through path A. We found a proper chiral *N,N′*-dioxide ligand was essential for the success.

Initially, keto ester **1a** and pent-4-yn-1-ol[15] (**2a**) were chosen as the model substrates to optimize the reaction conditions. At first, the complex of $Yb(OTf)_3$ or $Cu(OTf)_2$ coordinated to **L-PiEt$_2$** gave both the spiroketal *endo*-**3a** and fused bicyclo-[4.3.0] ketal **4a** (Table 1, entries 1–2). To our delight, the **L-PiEt$_2$**:$Ni(ClO_4)_2{\cdot}6H_2O$ complex was much better at promoting the reaction, and the expected product *endo*-**3a** was obtained with 93% *ee* (entry 3; 60% total yield of *endo*-**3a** and **4a**, *endo*-**3a**:**4a** = 95:5). The minor product *exo*-**3a** was obtained in 19% yield with 82% *ee*. Next, the screening of ligand suggested that more sterically hindered substituents at the *ortho* positions of aniline were beneficial to improve both chemoselectivities and *ee* values (entry 5 versus entries 3 and 4). The use of (*S*)-proline derived **L-PrPr$_2$** and (L)-ramipril derived **L-RaPr$_2$** resulted in lower chemoselectivities and poorer enantioselectivities than (*S*)-pipecolic acid derived **L-PiPr$_2$** (entries 6–7 versus entry 5). When the reaction was performed in $CHCl_3$, the desired major product *endo*-**3a** was isolated in 76% yield with 98% *ee* and the formation of **4a** was almost completely suppressed (entry 8). The minor isomer *exo*-**3a** was obtained with 18% yield and 94% *ee*. Unfortunately, all efforts to improve the diastereoselectivity by fine-tuning other reaction conditions, such as additives and π-acids, were unsuccessful (d.r. = *endo*:*exo*; see the Supporting Information for details).[16] Therefore, the optimized conditions involved the use of **L-PiPr$_2$**:$Ni(ClO_4)_2{\cdot}6H_2O$ and $AuCl{\cdot}PPh_3$ as catalysts in $CHCl_3$ at 35 °C for 24 h (entry 8).

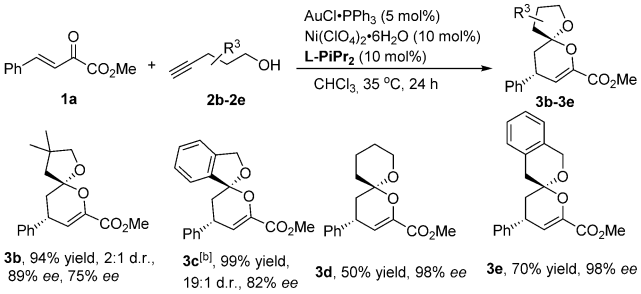
Table 1: Optimization of the reaction conditions.[a]



Entry	Metal	Ligand	Yield [%][b] *endo*-**3a**+**4a**/*exo*-**3a**	Ratio *endo*-**3a**:**4a**[c]	*ee* [%][c] *endo*-**3a**/**4a**/*exo*-**3a**
1	$Y(OTf)_3$	**L-PiEt$_2$**	82/–	40:60	43/64/–
2	$Cu(OTf)_2$	**L-PiEt$_2$**	99/–	43:57	74/61/–
3	$Ni(ClO_4)_2{\cdot}6H_2O$	**L-PiEt$_2$**	60/19	95:5	93/–/82
4	$Ni(ClO_4)_2{\cdot}6H_2O$	**L-PiMe$_2$**	77/22	86:14	84/75/66
5	$Ni(ClO_4)_2{\cdot}6H_2O$	**L-PiPr$_2$**	64/16	99:1	97/–/91
6	$Ni(ClO_4)_2{\cdot}6H_2O$	**L-PrPr$_2$**	50/34	78:22	91/74/85
7	$Ni(ClO_4)_2{\cdot}6H_2O$	**L-RaPr$_2$**	62/11	70:30	91/84/85
8[d]	$Ni(ClO_4)_2{\cdot}6H_2O$	**L-PiPr$_2$**	76/18	>99:1	98/–/94

[a] Unless otherwise noted, all reactions were carried out with **1a** (0.1 mmol), **2a** (0.15 mmol), **L**:$Ni(ClO_4)_2{\cdot}6H_2O$ (10 mol%:10 mol%), and $AuCl{\cdot}PPh_3$ (5 mol%) in CH_2Cl_2 (0.5 mL) at 35 °C for 24 h. [b] Total yield of isolated product *endo*-**3a**+**4a** given, as well as the yield of isolated *exo*-**3a**. [c] The *endo*-**3a**:**4a** ratio and *ee* values were determined by HPLC on a chiral stationary phase. [d] $CHCl_3$ was used as solvent instead of CH_2Cl_2.

Table 2: Substrate scope for the reaction between alkynyl alcohols and **1a**.[a]

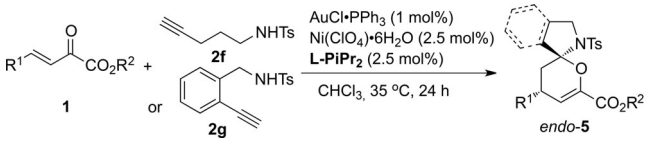


[a] Unless otherwise noted, all reactions were carried out with **1a** (0.1 mmol), **2** (0.15 mmol), $AuCl{\cdot}PPh_3$ (5 mol%), and **L-PiPr$_2$**:$Ni(ClO_4)_2{\cdot}6H_2O$ (10 mol%:10 mol%) in $CHCl_3$ (0.5 mL) at 35 °C for 24 h. The yield of the isolated product is given. The *ee* values were determined by HPLC on a chiral stationary phase and d.r. values were determined by ^1H NMR spectroscopy. [b] **2c** (0.11 mmol) was used.

Next, the generality of the procedure for different alkynyl alcohols was explored (Table 2). The 2,2-disubstituted 4-pentynol **2b** reacted smoothly with keto ester **1a**, generating the corresponding product **3b** in 94% yield (d.r. = 2:1, 89%/75% *ee*). The further exploration of reaction generality revealed that (2-ethynylphenyl)methanol **2c** was more reactive, and the desired product **3c** was obtained in nearly quantitative yield with excellent d.r. and moderate *ee* values. This result indicated that a bulkier phenyl substituent on alkynyl alcohol was beneficial for the diastereoselectivity. Additionally, hex-5-yn-1-ol (**2d**) and phenyl-substituted 5-hexynol **2e** were also effective, affording spiroketals **3d** in 50% yield with 98% *ee* and **3e** in 70% yield with 98% *ee*. The substrate scope of different keto esters with **2a** was also examined (6 examples, 77–99% yield, 2.0:1–3.3:1 d.r., 94–99% *ee*; see the Supporting Information for details). In all cases the chemoselectivity was very good and only the spiroketal isomers were detected. The diastereoselectivity was moderate, but both isomers could be isolated by flash chromatography.

Encouraged by the results obtained with alkynyl alcohols, we turned our attention to alkynyl amides (Table 3). The alkynyl amide **2f** showed a higher reactivity than alkynyl alcohol, and the desired spiroaminals could be obtained in high yields with excellent *ee* values with a lower catalyst loading (2.5 mol%). In all cases, higher d.r. values[17] were obtained

Table 3: Substrate scope for the reaction of keto esters with alkynyl amides.[a]

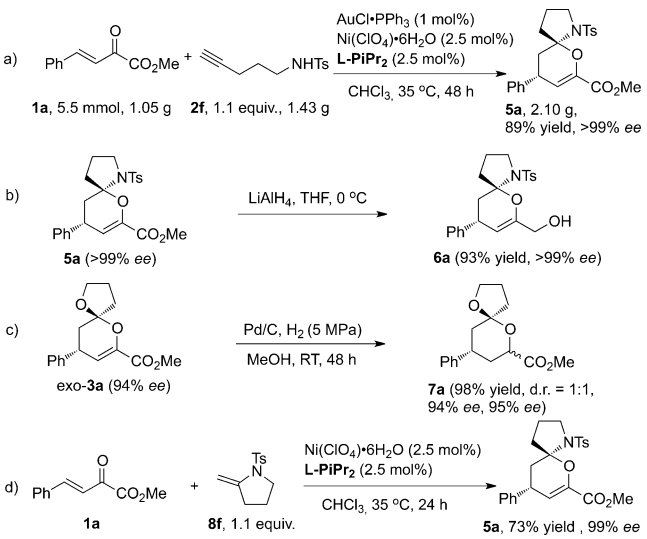


Entry	R^1, R^2	5	Yield [%][b]	*ee* [%][c]
1	Ph, Me	**5a**	87	>99 (*R*,*R*)[d]
2	Ph, *i*Pr	**5b**	71	99 (*R*,*R*)
3	Ph, Bn	**5c**	85	98 (*R*,*R*)
4[e]	2-MeC_6H_4, Me	**5d**	85	>99 (*R*,*R*)
5[e]	2-OMeC_6H_4, Me	**5e**	70	>99 (*R*,*R*)
6	3-OMeC_6H_4, Me	**5f**	91	>99 (*R*,*R*)
7	4-OMeC_6H_4, Me	**5g**	76	>99 (*R*,*R*)
8	4-MeC_6H_4, Me	**5h**	89	>99 (*R*,*R*)
9	4-FC_6H_4, Me	**5i**	84	>99 (*R*,*R*)
10	4-ClC_6H_4, Me	**5j**	84	>99 (*R*,*R*)
11	4-BrC_6H_4, Me	**5k**	79	>99 (*R*,*R*)
12[e]	2,6-$Me_2C_6H_3$, Me	**5l**	72	>99 (*R*,*R*)
13[e]	2-naphthyl, Me	**5m**	77	>99 (*R*,*R*)
14[e]	2-thienyl, Me	**5n**	83	>99 (*R*,*R*)
15[e]	cyclohexyl, Me	**5o**	80	99 (*R*,*S*)
16[f]	*n*Bu, Me	**5p**	34	96
17[g]	Ph, Me	**5q**	82	80

[a] Unless otherwise noted, all reactions were carried out with **1** (0.1 mmol), **2f** (0.11 mmol), AuCl·PPh_3 (1 mol%), and **L-PiPr$_2$**:Ni$(ClO_4)_2$·6H_2O (2.5 mol%:2.5 mol%) in $CHCl_3$ (0.25 mL) at 35 °C for 24 h. [b] Yield of isolated product. High d.r. values were obtained and we just collected the major diastereomer *endo*-**5**. [c] Determined by HPLC on a chiral stationary phase. [d] The absolute configuration of **5a** was determined to be (5*R*, 9*R*) by X-ray crystallographic analysis and the absolute configurations of other products were also determined by comparing their circular dichroism spectra with that of **5a**. [e] Reaction carried out for 48 h. [f] **L-PiPr$_2$**:Ni$(ClO_4)_2$·6H_2O (10 mol%:10 mol%) and AuCl·PPh_3 (5 mol%). [g] **2g** was used instead of **2f**, reaction carried out at 30 °C for 96 h.

and the minor diastereomer was inseparable from the byproduct, so only the major diastereomer *endo*-**5** was collected. The desired spiroaminal **5a**[18] was obtained in 87% yield with >99% *ee* (entry 1). When the methyl ester group of the keto esters was replaced by a bulkier aliphatic *i*Pr or benzyl group, the *ee* values remained excellent and the yields were still high (71–85% yield, 98–99% *ee*; entries 2–3). The steric hindrance and electronic properties resulting from the incorporation of an aromatic ring on the keto esters had no effect on the efficiency of the cascade reaction. Good yields (70–91%) with excellent enantioselectivities (>99% *ee*) were obtained (entries 4–12). Ring-condensed **1m** and heteroaromatic **1n** were also suitable substrates, offering **5m** in 77% yield and **5n** in 83% yield with more than 99% *ee* in both cases (entries 13–14). Moreover, the aliphatic cyclohexyl **1o** and *n*-butyl-substituted **1p** were also suitable substrates for the reaction (entries 15–16; 34–80% yield, 96–99% *ee*). Notably, phenyl-substituted alkynyl amide **2g** was also tolerated under a lower reaction temperature because product **5q** was unstable (entry 17; 82% yield, 80% *ee*).

To show the synthetic utility of the catalyst system, the cascade reaction of keto ester **1a** and alkynyl amide **2f** was performed on a gram scale. The desired product **5a** was obtained in 89% yield with more than 99% *ee* (Scheme 2a).



Scheme 2. a) Asymmetric cascade reaction on a gram scale; b) Transformation of ester **5a** to alcohol **6a**; c) Reduction of compound *exo*-**3a** with H_2; d) Control experiment.

The reduction of **5a** with $LiAlH_4$ generated the corresponding alcohol **6a** in 93% yield with more than 99% *ee*. Hydrogenation of the dihydro-*2H*-pyran ring in the presence of Pd/C occurred smoothly and the desired tetrahydropyran product **7a** was obtained as a mixture of diastereomers in 98% yield, 1:1 d.r. and without loss of enantioselectivity. The cyclization enamide **8f**[19] reacted efficiently with keto ester **1a** to furnish the corresponding spiroaminal **5a** in 73% yield with 99% *ee* which indicated that the possible reaction pathway is the gold-catalyzed hydroamination and chiral Lewis acid catalyzed IED hetero-DA reaction cascade (Scheme 2d).

In light of the X-ray structure of the *N*,*N*′-dioxide Ni^{II} complex[14d] and the absolute configuration of the product **5a**,[18] a catalytic model is proposed for the IED hetero-DA reaction (Figure 1). The tetradentate *N*,*N*′-dioxides **L-PiPr$_2$** and the bidentate keto ester **1a** coordinate to the Ni^{II} center to form a complex with octahedral geometry as the intermediate **TS**. The *Re* face of the keto ester is shielded by the neighboring amide group of the ligand and the enamide attack takes place from the *Si* face of the keto ester to form the *endo*-**5a**. The *exo*-**5a** was disfavored because of the steric hindrance between the ligand and the Ts group.

In summary, a highly efficient asymmetric cascade reaction of keto esters with alkynyl alcohols and amides has been realized for the first time by using a bimetallic gold(I)/chiral *N*,*N*′-dioxide nickel(II) complex catalyst system. The corresponding spiroketals and spiroaminals rather than fused bicyclo products were obtained in good yields, moderate to high diastereoselectivity, and excellent enantioselectivity under mild conditions. Extensive exploration of the bimetallic catalyst system for other asymmetric reactions is under way.

Experimental Section

Conditions: Ni$(ClO_4)_2$·6H_2O (10 mol%), *N*,*N*′-dioxide ligand **L-PiPr$_2$** (10 mol%), AuCl·PPh_3 (5 mol%) and keto ester **1a** (0.10 mmol) were stirred in $CHCl_3$ (0.5 mL) at 35 °C for 0.5 h. Then substrate **2a**

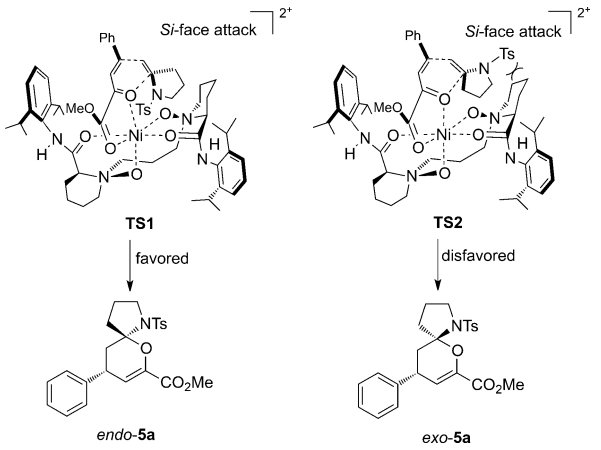


Figure 1. Proposed transition state. Ts = tosylate.

(0.15 mmol) were added. The reaction was stirred at 35 °C for 24 h, and then directly purified by flash chromatography on silica gel (petroleum ether/ethyl ether = 6/1) to afford the desired product *exo*-**3a** and *endo*-**3a**.

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[1] For selected reviews, see: a) A. E. Allen, D. W. C. MacMillan, *Chem. Sci.* **2012**, *3*, 633 – 658; b) L. Chen, Y.-L. Liu, J. Zhou, *Multicatalyst System in Asymmetric Catalysis: Asymmetric Cooperative Catalysis*, 1st ed., Wiley-VCH, Weinheim, **2014**, pp. 291 – 371; c) S. M. Inamdar, V. S. Shinde, N. T. Patil, *Org. Biomol. Chem.* **2015**, *13*, 8116 – 8162; d) G. Jindal, H. K. Kisan, R. B. Sunoj, *ACS Catal.* **2015**, *5*, 480 – 503.

[2] For selected reviews, see: a) Z. Shao, H. Zhang, *Chem. Soc. Rev.* **2009**, *38*, 2745 – 2755; b) C. Zhong, X. Shi, *Eur. J. Org. Chem.* **2010**, 2999 – 3025; c) C. C. J. Loh, D. Enders, *Chem. Eur. J.* **2012**, *18*, 10212 – 10225; d) Z. Du, Z. Shao, *Chem. Soc. Rev.* **2013**, *42*, 1337 – 1378.

[3] a) G. Chen, Y. Deng, L.-Z. Gong, A. Mi, X. Cui, Y. Jiang, M. C. K. Choi, A. S. C. Chan, *Tetrahedron: Asymmetry* **2001**, *12*, 1567 – 1571; b) M. Nakoji, T. Kanayama, T. Okino, Y. Takemoto, *Org. Lett.* **2001**, *3*, 3329 – 3331.

[4] For selected reviews, see: a) M. Rueping, R. M. Koenigs, I. Atodiresei, *Chem. Eur. J.* **2010**, *16*, 9350 – 9365; b) S. Zhang, F. Wei, C. Song, J. Jia, Z. Xu, *Chin. J. Chem.* **2014**, *32*, 937 – 956; c) D.-F. Chen, Z.-Y. Han, X.-L. Zhou, L.-Z. Gong, *Acc. Chem. Res.* **2014**, *47*, 2365 – 2377; d) Z.-P. Yang, W. Zhang, S.-L. You, *J. Org. Chem.* **2014**, *79*, 7785 – 7798.

[5] a) I. Ibrahem, A. Cordova, *Angew. Chem. Int. Ed.* **2006**, *45*, 1952 – 1956; *Angew. Chem.* **2006**, *118*, 1986 – 1990; b) A. E. Allen, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2010**, *132*, 4986 – 4987; c) Z. Xu, L. Liu, K. Wheeler, H. Wang, *Angew. Chem. Int. Ed.* **2011**, *50*, 3484 – 3488; *Angew. Chem.* **2011**, *123*, 3546 – 3550; d) S. Krautwald, D. Sarlah, M. A. Schafroth, E. M. Carreira, *Science* **2013**, *340*, 1065 – 1068.

[6] a) C. Arróniz, A. Gil-González, V. Semak, C. Escolano, J. Bosch, M. Amat, *Eur. J. Org. Chem.* **2011**, 3755 – 3760; b) L. Stegbauer, F. Sladojevich, D. J. Dixon, *Chem. Sci.* **2012**, *3*, 942 – 958.

[7] a) D. E. A. Raup, B. Cardinal-David, D. Holte, K. A. Scheidt, *Nat. Chem.* **2010**, *2*, 766 – 771; b) J. Mo, X. Chen, Y. R. Chi, *J. Am. Chem. Soc.* **2012**, *134*, 8810 – 8813; c) Z. J. Wu, F. Y. Li, J. Wang, *Angew. Chem. Int. Ed.* **2015**, *54*, 1629 – 1633; *Angew. Chem.* **2015**, *127*, 1649 – 1653.

[8] a) G. Jiang, B. List, *Angew. Chem. Int. Ed.* **2011**, *50*, 9471 – 9474; *Angew. Chem.* **2011**, *123*, 9643 – 9646; b) R. De Vreese, M. D'hooghe, *Beilstein J. Org. Chem.* **2012**, *8*, 398 – 402.

[9] a) B. K. Corkey, F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 17168 – 17169; b) X.-Y. Guan, L.-P. Yang, W. H. Hu, *Angew. Chem. Int. Ed.* **2010**, *49*, 2190 – 2192; *Angew. Chem.* **2010**, *122*, 2236 – 2238; c) M. Ikeda, Y. Miyake, Y. Nishibayashi, *Chem. Eur. J.* **2012**, *18*, 3321 – 3328; d) F. Nahra, Y. Macé, D. Lambin, O. Riant, *Angew. Chem. Int. Ed.* **2013**, *52*, 3208 – 3212; *Angew. Chem.* **2013**, *125*, 3290 – 3294; e) Y. Z. Wang, L. Z. Liu, L. M. Zhang, *Chem. Sci.* **2013**, *4*, 739 – 746; f) S. Matsunaga, M. Shibasaki, *Chem. Commun.* **2014**, *50*, 1044 – 1057; g) A. A. Friedman, J. Panteleev, J. Tsoung, V. Huynh, M. Lautens, *Angew. Chem. Int. Ed.* **2013**, *52*, 9755 – 9758; *Angew. Chem.* **2013**, *125*, 9937 – 9940; h) L. Zhang, Z. Qureshi, L. Sonaglia, M. Lautens, *Angew. Chem. Int. Ed.* **2014**, *53*, 13850 – 13853; *Angew. Chem.* **2014**, *126*, 14070 – 14073.

[10] For selected reviews on gold catalysis, see: a) A. S. K. Hashmi, *Angew. Chem. Int. Ed.* **2010**, *49*, 5232 – 5241; *Angew. Chem.* **2010**, *122*, 5360 – 5369; b) Y.-M. Wang, A. D. Lackner, F. D. Toste, *Acc. Chem. Res.* **2014**, *47*, 889 – 901; c) B. Alcaide, P. Almendros, *Acc. Chem. Res.* **2014**, *47*, 939 – 952.

[11] a) M. Suzuki, R. Ueoka, K. Takada, S. Okada, S. Ohtsuka, Y. Ise, S. Matsunaga, *J. Nat. Prod.* **2012**, *75*, 1192 – 1195; b) L. A. MacKenzie, A. I. Selwood, C. Marshall, *Toxicon* **2012**, *60*, 406 – 419; c) J. Sperry, Z. E. Wilson, D. C. K. Rathwell, M. A. Brimble, *Nat. Prod. Rep.* **2010**, *27*, 1117 – 1137.

[12] a) J. Han, B. Xu, G. B. Hammond, *J. Am. Chem. Soc.* **2010**, *132*, 916 – 917; b) J. Han, B. Xu, G. B. Hammond, *Org. Lett.* **2011**, *13*, 3450 – 3453.

[13] a) X. Wang, Z. Yao, S. Dong, F. Wei, H. Wang, Z. Xu, *Org. Lett.* **2013**, *15*, 2234 – 2237; b) X. Wang, S. Dong, Z. Yao, L. Feng, P. Daka, H. Wang, Z. Xu, *Org. Lett.* **2014**, *16*, 22 – 25; c) S. Zhang, Z. Xu, J. Jia, C.-H. Tung, Z. Xu, *Chem. Commun.* **2014**, *50*, 12084 – 12087.

[14] For representative reviews and example of *N*,*N*′-dioxide–metal complexes, see: a) X. H. Liu, L. L. Lin, X. M. Feng, *Acc. Chem. Res.* **2011**, *44*, 574 – 587; b) K. Shen, X. H. Liu, L. L. Lin, X. M. Feng, *Chem. Sci.* **2012**, *3*, 327 – 334; c) X. H. Liu, L. L. Lin, X. M. Feng, *Org. Chem. Front.* **2014**, *1*, 298 – 302; d) K. Zheng, X. H. Liu, J. N. Zhao, Y. Yang, L. L. Lin, X. M. Feng, *Chem. Commun.* **2010**, *46*, 3771 – 3773.

[15] a) Z.-Y. Han, R. Guo, P.-S. Wang, D.-F. Chen, H. Xiao, L.-Z. Gong, *Tetrahedron Lett.* **2011**, *52*, 5963 – 5967; b) H. Wu, Y.-P. He, L.-Z. Gong, *Org. Lett.* **2013**, *15*, 460 – 463.

[16] H. Audrain, J. Thorhauge, R. G. Hazell, K. A. Jørgensen, *J. Org. Chem.* **2000**, *65*, 4487 – 4497.

[17] A higher d.r. value could be obtained as a result of steric hindrance.

[18] CCDC 1437956 (**5a**) contains the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

[19] Enamide **8f** is very reactive and could not be isolated under the current catalytic system. Enamide **8f** was synthesized by another method, see: H. Lu, X. Yuan, S. Zhu, C. Sun, C. Li, *J. Org. Chem.* **2008**, *73*, 8665 – 8668.

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