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Facile access to chiral γ-butyrolactones *via* rhodium-catalysed asymmetric hydrogenation of γ-butenolides and γ-hydroxybutenolides†

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The highly efficient Rh/ZhaoPhos-catalysed asymmetric hydrogenation of γ-butenolides and γ-hydroxybutenolides was successfully developed. This protocol provides an efficient and practical approach to the synthesis of various chiral γ-butyrolactones, which are synthetically valuable building blocks of diverse natural products and therapeutic substances, with excellent results (up to >99% conversion and 99% ee). Further follow-up transformations have been revealed to accomplish creative and efficient synthetic routes for several enantiomerically enriched drugs *via* this catalytic methodology.

γ-Butyrolactone is an essential framework existing in large numbers of natural products[1] and pharmaceutical compounds[2] and shows unique and excellent biological activities (Fig. 1). Furthermore, enantiomerically pure γ-butyrolactones could serve as building blocks for the construction of a wide range of complex molecules,[3] and diverse transformations have been developed,[4] especially in the highly versatile furanone structure, to synthesize physiologically and therapeutically important reagents, for example brivaracetam,[5] arctigenin,[6] pilocarpine,[7] *etc.*

As commercially available or easily accessible compounds, γ-butenolides[8] are important synthetic precursors towards γ-butyrolactones, and an impressive range of transformations have been developed for the enantioselective construction of chiral γ-butyrolactones.[9] With the advancement in the field of asymmetric metal catalysis, enantioselective 1,4-addition and reduction of γ-butenolides have been considered representative methodologies of preparing optically active γ-butyrolactones. In contrast to the well-developed asymmetric 1,4-additions[10] (Scheme 1a), with transition metal-catalysed 1,4-reduction of γ-butenolides as an alternative it would be difficult to achieve satisfactory catalytic conversion and stereoselectivity as well as broad substrate scope because of the lack of efficient metal catalysts.[11] The Buchwald group reported a CuH-catalysed enantioselective conjugate reduction of γ-butenolides;[12] however, the requirement of using high catalyst loading and a strong base additive could limit the application of this method in organic synthesis and the pharmaceutical industry. Recently, our group developed a bisphosphine-thiourea chiral ligand, ZhaoPhos,[13] which exhibited extraordinary potential in rhodium[14] and iridium-catalyzed[15] asymmetric hydrogenation due to its powerful hydrogen-bonding and anion-binding ability resulting from the thiourea moiety. Inspired by this novel strategy, we herein demonstrated a Rh/ZhaoPhos catalysed asymmetric hydrogenation of easily accessible γ-butenolides and γ-hydroxybutenolides, which could be a straightforward method of approaching chiral γ-butyrolactones with excellent catalytic results (Scheme 1b).

We initiated our investigation with evaluation of various combinations of the rhodium precatalyst and different chiral phosphine ligands for the asymmetric hydrogenation of 4-phenylfuran-2(5*H*)-one **1a**. After examining a series of commonly used chiral phosphine ligands and using THF as the

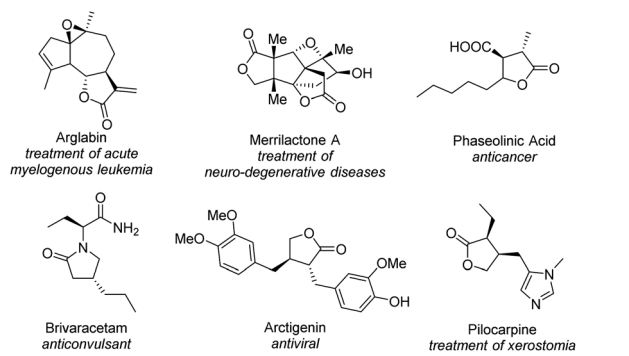

Fig. 1 Natural products containing the γ-butyrolactone core, and pharmaceutical compounds derived from γ-butyrolactones.

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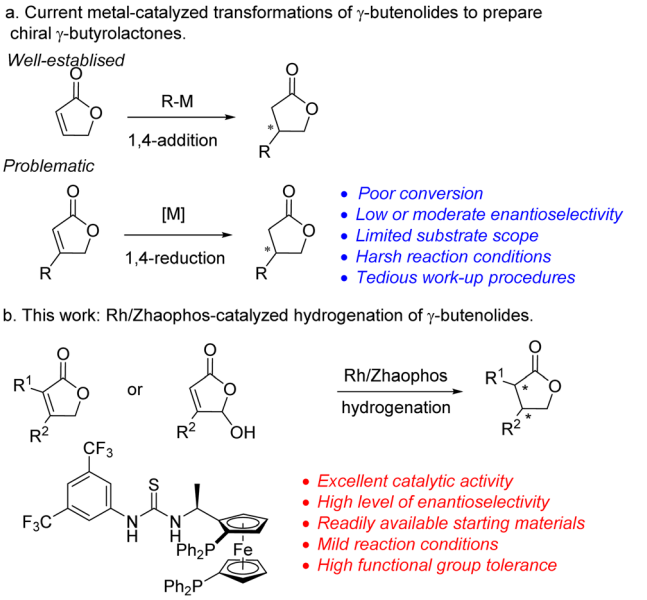
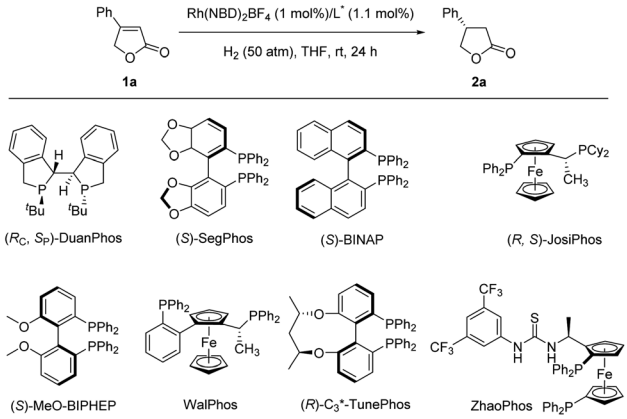


Scheme 1 Current methods of preparing chiral γ-butyrolactones from γ-butenolides, and proposed Rh/ZhaoPhos-catalyzed hydrogenation.

solvent, very poor enantioselectivity was achieved with ligands such as DuanPhos, SegPhos, BINAP and so on (Table 1, entries 1–7). Employing ZhaoPhos as a ligand could facilitate the hydrogenation with a significantly improved enantioselective manner, and the desired product **2a** was obtained in 79% conversion and 97% ee under 50 atm of H_2 at room temperature within 24 hours (entry 8). Furthermore, the solvent was crucial to the control of the reaction rate, and by screening several protic and aprotic solvents (Table 2, entries 1–9), we found that by employing DCM as solvent complete hydrogenation could be achieved under standard conditions, which afforded **2a** with >99% conversion and in 98% ee (entry 8).

With optimized reaction conditions in hand, we then continued to investigate the substrate generality (Table 3). A considerable number of β-aryl substituents (**2a–l**) on γ-butenolides were investigated, and the hydrogenation proceeded smoothly to yield the desired products with excellent yields (95 ~ 99%) and in high enantioselectivities (97 ~ 98% ee), in which both electron-withdrawing (**2b–2d**) and electron-donating (**2e–2j**) substituents on the aryl ring at different positions were well tolerated. The hydrogenation of substrates with the bulky naphthyl moiety (**1k**) and heterocyclic unit (thienyl, **1l**) was feasible, giving the corresponding product with excellent results (95 ~ 99% yields and 98% ee). In addition, the alkyl substituents (**2m–n**) were explored as well, and it is noteworthy that α-methyl substituted lactone **2n** could be produced with 84% or 82% ee respectively from the substrates featuring either endo- (**1n**) or exocyclic (**1n′**) unsaturation, in which this transformation was rarely achieved with good yield and in acceptable enantioselectivity according to previous studies.[16] The reactions of α,β-disubstituted γ-butenolides **1o** and **1p** were also conducted; however, no desired products were obtained.

Table 1 Ligand screening for the asymmetric hydrogenation of **1a**

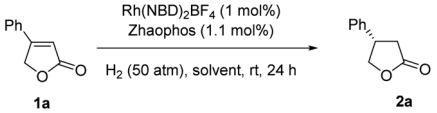


Entry[a]	Ligand	Conv.[b] (%)	ee[c] (%)
1	(R_C,S_P)-DuanPhos	14	1
2	(*S*)-SegPhos	100	2
3	(*S*)-BINAP	78	0
4	(*R*,*S*)-JosiPhos	100	2
5	(*R*)-MeO-BIPHEP	13	10
6	WalPhos	31	16
7	(*R*)-C_3*-TunePhos	8	13
8	***ZhaoPhos***	***79***	***97***

[a] Unless otherwise noted, all hydrogenations were carried out with a $[Rh(NBD)_2BF_4]$/ligand/**1a** (0.1 mmol) ratio of 1 : 1.1 : 100 in 1.0 mL of THF under H_2 (50 atm) at room temperature for 24 h. [b] Determined by ^1H NMR. [c] Determined by HPLC analysis, and the absolute configuration of **2a** was determined as *S* by comparing the optical rotation data with the literature.

Apart from the hydrogenation of γ-butenolides, γ-hydroxybutenolides **3** were also successfully reduced under the same reaction conditions with CF_3COOH as an additive (see the ESI†

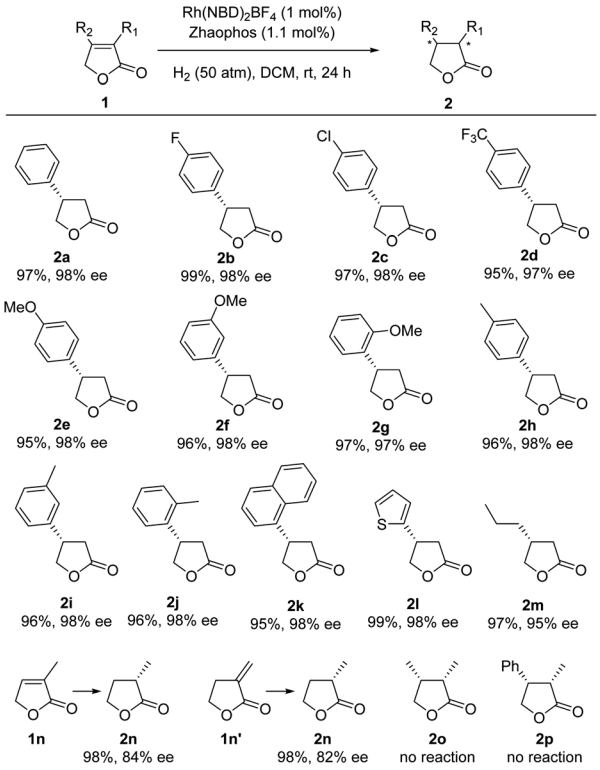
Table 2 Solvent screening for the asymmetric hydrogenation of **1a**



Entry[a]	Solvent	Conv.[b] (%)	ee[c] (%)
1	MeOH	29	96
2	EtOH	19	97
3	CF_3CH_2OH	59	98
4	EtOAc	>99	97
5	Toluene	91	95
6	THF	79	97
7	1,4-Dioxane	30	16
8	***DCM***	***>99***	***98***
9	DCE	25	96

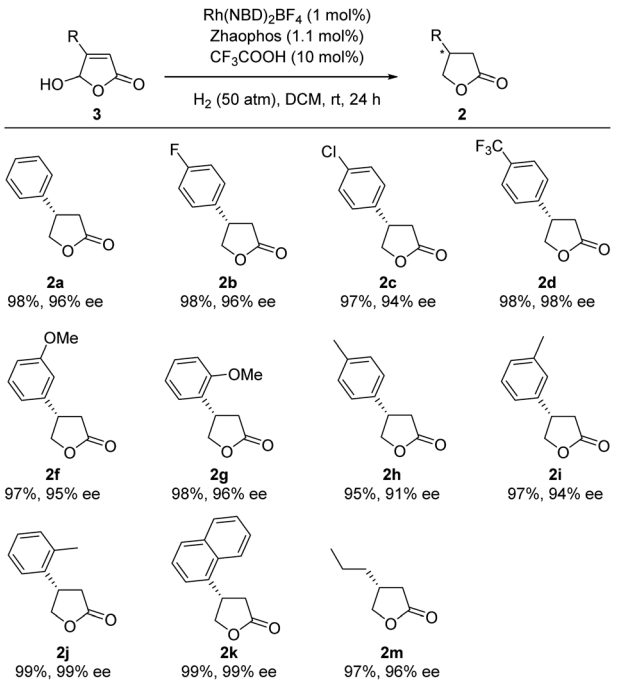
[a] Unless otherwise noted, all hydrogenations were carried out with a $[Rh(NBD)_2BF_4]$/ligand/**1a** (0.1 mmol) ratio of 1 : 1.1 : 100 in 1.0 mL of solvent under H_2 (50 atm) at room temperature for 24 h. [b] Determined by ^1H NMR. [c] Determined by HPLC analysis, and the absolute configuration of **2a** was determined as *S* by comparing the optical rotation data with the literature.

Table 3 Substrate scope of the hydrogenation of γ-butenolides **1** [a,b,c]



[a] Unless otherwise noted, all hydrogenations were carried out with a [Rh(NBD)$_2$BF$_4$]/ligand/**1a** (0.1 mmol) ratio of 1 : 1.1 : 100 in 1.0 mL of DCM under H_2 (50 atm) at room temperature for 24 h. [b] Isolated yield. [c] Determined by HPLC analysis, and the absolute configuration was determined by comparing the optical rotation data with the literature.

Table 4 Substrate scope of the hydrogenation of γ-hydroxybutenolides **3** [a,b,c]

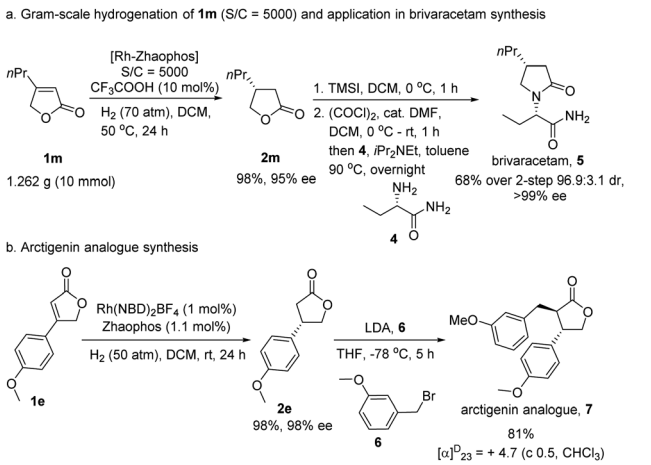


[a] Unless otherwise noted, all hydrogenations were carried out with a [Rh(NBD)$_2$BF$_4$]/ligand/CF_3COOH/**1a** (0.1 mmol) ratio of 1 : 1.1 : 10 : 100 in 1.0 mL of DCM under H_2 (50 atm) at room temperature for 24 h. [b] Isolated yield. [c] Determined by HPLC analysis, and the absolute configuration was determined comparing the optical rotation data with the literature.

for details), and consequently afforded γ-butyrolactones **2** directly in high yields (95 ∼ 99%) and with excellent enantioselectivities (up to 99% ee) (Table 4). We suggested that CF_3-COOH could activate the hydroxy group of lactol, which could be protonated to form an oxonium salt, and then hydrogenated by the catalyst.[15e,f] γ-Hydroxybutenolides could be naturally occurring as well as easily prepared, and on account of realizing these transformations, the scope of the starting material for preparing chiral γ-butyrolactones was extremely expanded, which further improved the synthetic value of the Rh/ZhaoPhos catalyst in the field of asymmetric hydrogenation.

To demonstrate the synthetic utilities of this method, a gram-scale hydrogenation of substrate **1m** (Scheme 2a) was conducted with a low catalyst loading of 0.02 mol%. To our delight, the hydrogenation underwent smoothly under 70 atm of H_2 at 50 °C using CF_3COOH (10 mol%) as the additive (adding CF_3COOH could not only stabilize the cationic rhodium catalyst to increase the TON of the reaction, but also activate the carbonyl of α,β-unsaturated lactone to facilitate the hydrogenation), and the chiral γ-butyrolactone **2m** was afforded in 98% yield and with 95% ee. We further transformed this chiral building block *via* a ring-opening/recyclization strategy to achieve the total synthesis of brivaracetam in high optical purity (96.9 : 3.1 dr and >99% ee) within only 3 steps (67% overall yield). Moreover, the 2-step synthesis of arctigenin analogue 7 was realized using γ-butenolide **1e** as the starting material (79% overall yield, Scheme 2b), which presented a shorter synthetic route compared to previous studies.[6c]

In summary, we have developed a highly enantioselective Rh/ZhaoPhos-catalyzed hydrogenation, providing a series of



Scheme 2 Synthetic applications.

synthetically useful chiral γ-butyrolactones with readily available γ-butenolides and γ-hydroxybutenolides as starting materials. In addition, this strategy was applicable to the construction of various natural products and therapeutic substances, and scalable and concise syntheses of the pharmaceutical drugs brivaracetam and arctigenin were accomplished through this methodology, which demonstrated its practical utilities.

Data availability

All experimental procedures, characterization, and computational data for this study, can be found in the ESI.†

Author contributions

The manuscript was written through the contributions of all authors. All authors have approved the final version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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