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Enantioselective one-pot synthesis of 4*H*chromene derivatives catalyzed by a chiral Ni(II) complex[†]

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A Ni(II)–bis(oxazoline) complex and *p*-TSOH are used to form enantioenriched 4*H*-chromenes from *ortho*quinone methides (*o*-QMs) and dicarbonyls, providing the desired products in up to 95% ee. The method is compatible with various β -ketoester substrates, and the products obtained could be converted into biologically active 4*H*-chromene derivatives.

The chromene skeleton is widespread in natural products and medicinal agents,¹ and the diverse biological activities² of chromene derivatives have intrigued pharmacologists and chemists. In particular, 4*H*-chromene is a privileged core structure that has received increasing attention in recent years. Natural and synthetic functionalized 4*H*-chromenes (Fig. 1) display a broad spectrum of biological activities,³ including as cell-proliferation inhibitors (**A**), apoptosis inducers (**B**), and neuropeptide Y Y5 receptor antagonists (**C**), as well as improving cognitive deficit (**D**).

Over the past decade, extensive efforts have been devoted to the synthesis of 4*H*-chromene compounds. Most of the synthetic methods furnished racemic products,^{4,5} though enantioselective routes have recently been developed. In 2009 and 2011, Xie *et al.* and



Fig. 1 Natural and synthetic bioactive 4H-chromene compounds.

Wang et al.⁶ respectively, reported the organocatalytic synthesis of chiral 2-amino-4H-chromene derivatives from malononitrile. In 2011, Feng et al.7 explored the first Lewis acid-catalyzed one-pot synthesis of enantioenriched 2-amino-4H-chromenes bearing indolyl moieties from malononitrile, salicylaldehyde and indole. In 2014, Schneider et al.8 found the reaction of ortho-hydroxyl benzhydryl alcohols with β-diketones was catalyzed by a chiral phosphoric acid (CPA), giving rise to 4H-chromenes in high yield with excellent enantioselectivities (up to 98% ee); however, when the substrate was changed to ethyl acetoacetate, the ee value dropped to 84%. Subsequently, Rueping et al.9 employed a chiral binol based Ntrifly phosphoramide to promote the in situ generation of orthoquinone methides (o-QMs) and their subsequent reaction with 1,3cyclohexanedione, providing the desired 4H-chromene products with excellent enantioselectivities (up to 95% ee). In 2017, the Schneider group reported the oxidation of 2-alkyl-substituted phenols in situ by $Mn(dbm)_3$ (dbm = dibenzoylmethane) to give o-QMs that, upon the CPA-catalyzed conjugate addition of β-dicarbonyls, afforded 4H-chromenes in up to 79% yield and up to 74% ee,10 indicating that the substrate structures have a remarkable influence on the reaction. Despite these notable advances, efficient and concise methods for the enantioselective synthesis of 4Hchromenes are still limited and highly desirable.

o-QMs have been extensively applied in Michael additions and cycloadditions.^{11,12} The reaction of some dicarbonyls with o-QMs generates chromene derivatives, and particularly the use of β -diketones has been well studied.

However, few reports mention the use of asymmetric catalysis to construct 4*H*-chromenes from β -ketoesters.^{8,13} As part of a continuing effort to develop efficient catalytic asymmetric methods using readily available catalyst systems,¹⁴ we explored the reaction of β -ketoesters with *o*-QMs catalyzed by a Ni(π)bis(oxazoline) complex and subsequent *p*-TSOH, which gave 4*H*-chromenes in good yields and up to 95% ee. This one-pot, three-step sequence of enantioselective Michael addition, intramolecular ketalization and dehydration, was accomplished

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under mild conditions. The products could be transformed into potentially bioactive 4*H*-chromene compounds.

At the outset, *ortho*-quinone methide (*o*-QMs) 1a (PMP = *p*-MeOPh) and ethyl acetoacetate 2a were chosen as model substrates. The reaction was carried out in CHCl₃ at 0 °C in the presence of different metal complexes of ligand L1. For various Lewis acids including Cu(OTf)₂, Mg(OTf)₂, Zn(OTf)₂, Ni(OTf)₂ and $Ni(ClO_4)_2$, the reaction proceeded to completion within 5 minutes and giving product 3aa in moderate to high yields (Table 1, entries 1-5). To our delight, Ni(OTf)₂ afforded the highest enantioselectivity (90% ee, entry 4). Encouraged by this result, the effect of solvent was tested. Other solvents did not show any positive effect on the reaction reactivity. Even the reaction was almost suppressed in tetrahydrofuran (THF) (Table 1, entry 8). Subsequently, different ligands were examined. No better results were achieved by Ni(OTf)₂ complexes of other bis(oxazoline) ligands. As expected, when lowering the reaction temperature to -40 °C the enantioselectivity could be improved to 95% ee regardless of a longer reaction time (entry 16). When the catalyst loading was reduced to 5 mol%, the reactivity was somewhat decreased although the enantioselectivity still

remained (entry 17). The detailed screening data are illustrated in ESI. †

Initial optimization employing ortho-QM 1a and ethyl acetoacetate 2a provided 3aa in 90% yield with 95% ee when the reaction was carried out at -40 °C in CHCl₃ using 10 mol% Ni(OTf)₂ and 11 mol% of the bis(oxazoline) L1 (Scheme 1); thus we used these conditions to explore the reaction scope for β dicarbonyl substrates (Scheme 1). The iso-propyl or benzyl acetoacetate reacted with o-quinone methide to furnish 4Hchromenes 3ab and 3ac in high yields and ee values similar to those obtained with the ethyl ester. β-Alkyl-substituents on the β-ketoesters were well tolerated, and a high level of enantioselectivity (86-93% ee for 3ad-3ag) was observed. Even a β-styrenyl substituted β -ketoester was also a suitable substrate, affording chromene **3ah** in 84% ee. Regrettably, when β -aryl-substituted β-ketoesters 2i and 2j were used, the product was obtained with markedly lower ee (70% ee for 3ai and 37% ee for 3ai). Moreover, the same high enantioselectivities were obtained from chain β -diketones, giving rise to **3ak** and **3al** in 89% and 93% ee. However, in the case of 1,3-cyclohexanedione only the racemic 4H-chromene was obtained. In addition, considering

Table 1 Optimization of the reaction condition ^a						
	PMP 		Et 1) Metal-Ligand Et 2) p -TsOH, 40°C, 1h PMP = p -MeOPh 3aa			AP
$\begin{array}{c} & & & & \\ & & & \\ & & & \\ & & \\ & & \\ & & \\ L1 R = Ph, L2 R = {}^{i}Pr \\ L3 R = {}^{i}Bu, L4 R = Bn \end{array} \qquad \begin{array}{c} & & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & $						
Entry	Ligand	Ni(II)	Solvent	Time	$\operatorname{Yield}^{b}(\%)$	$\mathrm{Ee}^{c}(\%)$
1	L1	Cu(OTf) ₂	$CHCl_3$	5 min	77	30
2	L1	$Mg(OTf)_2$	$CHCl_3$	5 min	65	6
3	L1	$Zn(OTf)_2$	$CHCl_3$	5 min	84	36
4	L1	$Ni(OTf)_2$	$CHCl_3$	5 min	85	90
5	L1	$Ni(ClO_4)_2$	$CHCl_3$	5 min	54	67
6	L1	$Ni(OTf)_2$	Toluene	5 min	56	90
7	L1	Ni(OTf) ₂₂	CH_2Cl_2	5 min	73	69
8	L1	$Ni(OTf)_2$	THF	5 min	Trace	_
9	L1	Ni(OTf) ₂₂	EtOAc	5 min	46	88
10	L2	$Ni(OTf)_2$	$CHCl_3$	5 min	67	60
11	L3	$Ni(OTf)_2$	$CHCl_3$	5 min	79	20
12	L4	$Ni(OTf)_2$	$CHCl_3$	5 min	66	55
13	L5	Ni(OTf) ₂	$CHCl_3$	5 min	88	52
14	L6	Ni(OTf) ₂₂	$CHCl_3$	5 min	75	26
15^d	L1	$Ni(OTf)_2$	$CHCl_3$	1 h	87	92
16 ^e	L1	Ni(OTf) ₂	CHCl ₃	3 h	90	95
17 ^{<i>j</i>}	L1	$Ni(OTf)_2$	$CHCl_3$	5 h	78	95

^{*a*} All reactions were carried out in solvent (1.5 mL) using 10 mol% metal salt and 11 mol% ligand under nitrogen for indicated time before *p*-TSOH (20 mol%) was added at 40 °C. ^{*b*} Isolated yields. ^{*c*} Determined by HPLC. ^{*d*} -20 °C. ^{*e*} -40 °C. ^{*f*} 5 mol% catalyst at -40 °C.



Scheme 1 The scope of β -dicarbonyls. ^aAll reactions were conducted in CHCl₃ (1.5 mL) using Ni(OTf)₂ (10 mol%) and L1 (11 mol%) at -40 °C under nitrogen for the indicated time before *p*-TSOH (20 mol%) was added at 40 °C; ^bisolated yields. ^cDetermined by HPLC.



Scheme 2 The scope of *o*-QMs. ^aAll reactions were conducted using Ni(OTf)₂ (10 mol%) and L1 (11 mol%) in CHCl₃ (1.5 mL) at -40 °C under nitrogen for the indicated time before *p*-TSOH (20 mol%) was added at 40 °C; ^{*b*} isolated yields; ^{*c*} determined by HPLC.

the structural similarity with β -ketoesters, β -keto amides as substrates were also subjected to the above reaction condition, regrettably, the reaction didn't occur.

We next turned our attention to varying the *o*-QMs. Dimethoxy-substituted *o*-QM **1b** was evaluated under optimal conditions (Scheme 2), In the case of ethyl acetacetate, the reaction was complete at -40 °C within 2 h, and subsequent treatment with TsOH led to the annulation product **3ba** in 87% yield and 84% ee. However the reaction of **1b** with β -diketones required much longer time (20–24 h) and was less stereo-selective (63% and 74% ee for **3bi** and **3bj**). Thus it is deducted that the substituents on both the quinone ring of the *o*-QMs and



Scheme 3 The extension to vinyl *o*-QMs. ^aAll reactions were conducted using Ni(OTf)₂ (10 mol%) and L1 (11 mol%) in CHCl₃ (1.5 mL) at -20 °C under nitrogen for the indicated time before *p*-TSOH (20 mol%) was added at 40 °C. ^bIsolated yields. ^cDetermined by HPLC.

 β -ketoester substrates have a remarkable impact on the reactivity and enantioselectivity.

The substrate scope could be expanded to other stable vinyl o-QMs.¹⁵ At -40 °C the reaction of α -substituted vinyl o-QMs with ethyl acetoacetate occurred very sluggishly, but upon raising the temperature to -20 °C, a series of α -substituted vinyl o-QMs could be used, as shown in Scheme 3. Substituted vinyl o-QMs containing electron-withdrawing groups (**1f-1h**) were incorporated into chromenes in much higher yield than those bearing electron-donating groups (**1d, 1e, and 1i**). For all cases, good to high enantioselectivities were achieved (80–92% ee, **3ca-3ia**). Vinyl o-QMs with thienyl or naphthyl rings on the olefin were also suitable reactants and provided the desired products **3ja** and **3ka** in moderate yields with high enantioselectivities (90% and 92% ee).

On the basis of X-ray diffraction analysis, the single crystal of compound 3ab was determined to be S (Fig. 2),¹⁶ and the configuration of other products was also assigned by analogy. Considering the observed stereochemistry, a plausible asymmetric induction model was proposed (Fig. 2). The coordination of bisoxazoline ligand L1 to a Ni(OTf)₂ resulted in a Ni(II)-L1 complex, which interacted with acetoacetate to form an enolate. Simultaneously, the o-QMs 1a also coordinated to the Ni(π) center from the axial direction. Steric congestion between the pmethoxyphenyl group of 1a and the phenyl substituent of ligand L1 disfavors an approach of the enolized acetoacetate to o-QMs from the Si-face, so the major product is formed from Re-face addition and subsequent treatment with p-TSOH form the Sisomer. Given the lower enantioselectivity afforded by β-arylsubstituted ketoesters in contrast to the corresponding alkyl group substrates, it is deducted that π - π stacking may be unfavorable for the asymmetric induction in the Michael addition step. The detailed mechanism remains to be further investigated.

The catalyst system was used to synthesize product **3aa** on a gram scale, in 85% yield and without compromising enantioselectivity (Scheme 4a). Treatment of product **3aa** with DIBALH (2.5 equiv.) in CH_2Cl_2 at -78 °C generated the corresponding alcohol **4**, which is an important intermediate; for example, subsequent reaction with DPPA/DBU resulted in azide



Fig. 2 Stereochemical induction model.

a) Scale-up reaction



Scheme 4 The scale-up reaction and transformation of the products.

compound 5 with a slight loss of enantiopurity (Scheme 4b, 90% ee).

Finally, attempts to employ the β -silyloxymethylenesubstituted β -ketoester 2k led to the discovery of an unexpected cascade reaction that yielded a pharmaceutically interesting molecule. Following the conjugate addition under standard conditions and treatment with p-TsOH, the chromene lactone 3ak was produced in 75% yield with 92% ee (Scheme 4c). Replacing the *p*-TsOH with other Brønsted acid or Lewis acids always yielded an intramolecular ketalization/dehydration accompanied by the deprotection of siloxyl group and subsequent intramolecular nucleophilic addition-elimination to give 3ak. To the best our knowledge, this is a rare example of one-pot five-step reaction under mild conditions. The racemate of 3ak is a potential inhibitor of tumor growth.^{2f}

In conclusion, the Ni(OTf)2/bis(oxazoline)-catalyzed asymmetric conjugate addition of β -dicarbonyls to *o*-OMs followed by treatment of p-TsOH generated 4H-chromenes in up to 95% ee. In particular, this method is amenable to the reaction of β -ketoesters, which well complements previous reports involving only 1,3diketone substrates in this type of reaction.8-10 Moreover, the catalytic products could be converted into biologically active and even pharmaceutically valuable 4H-chromene derivatives. Further application of this methodology is underway in our laboratory.

Conflicts of interest

There are no conflicts to declare.

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