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Dynamic kinetic resolution of γ,γ-disubstituted indole 2-carboxaldehydes *via* NHC-Lewis acid cooperative catalysis for the synthesis of tetracyclic ε-lactones†

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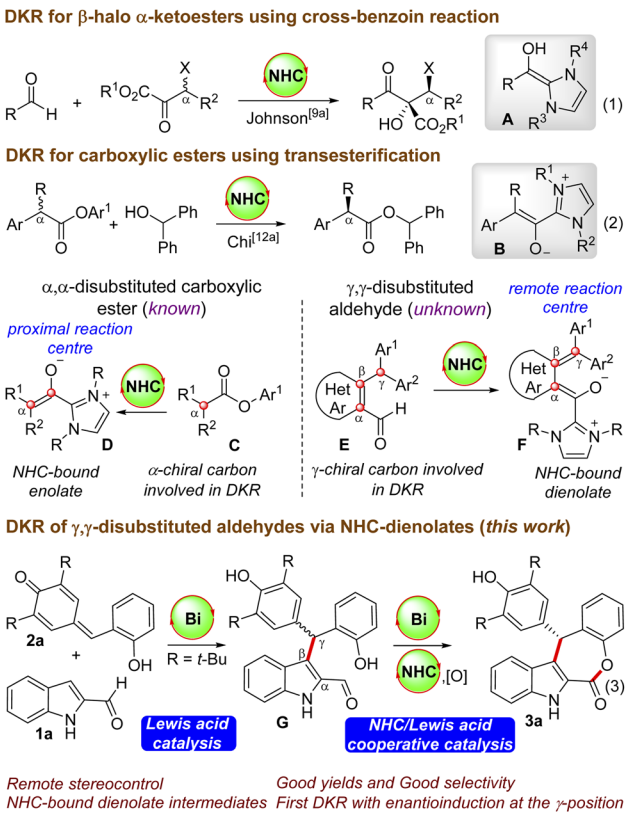
The ubiquity of ε-lactones in various biologically active compounds inspired the development of efficient and enantioselective routes to these target compounds. Described herein is the enantioselective synthesis of indole-fused ε-lactones by the N-heterocyclic carbene (NHC)-Lewis acid cooperative catalyzed dynamic kinetic resolution (DKR) of *in situ* generated γ,γ-disubstituted indole 2-carboxaldehydes. The $Bi(OTf)_3$-catalyzed Friedel–Crafts reaction of indole-2-carboxaldehyde with 2-hydroxy phenyl *p*-quinone methides generates γ,γ-disubstituted indole 2-carboxaldehydes, which in the presence of NHC and $Bi(OTf)_3$ afforded the desired tetracyclic ε-lactones in up to 93% yield and >99 : 1 er. Moreover, preliminary studies on the mechanism of this formal [4 + 3] annulation are also provided.

Introduction

Functionalized ε-lactones are important structural motifs present in various biologically active compounds and this core is responsible for the flavor and aroma in many natural products.[1] For instance, the natural products rubellins A and B have the benzo-fused ε-lactone moiety connected to the anthraquinone unit, and they exhibit photodynamic activity.[2] Moreover, 9-dehydroxyeurotinone and 2-*O*-methyl-9-dehydoxyeurotinone have a dibenzo-fused ε-lactone core, and they are useful due to their antimicrobial and cytotoxic activity.[3] Given the potential applications of ε-lactone-containing compounds, the development of rapid and facile routes for the enantioselective synthesis of ε-lactone derivatives have received remarkable attention. The Baeyer-Villiger oxidation of cyclohexanones constitutes one of the traditional approaches to access ε-lactones.[4] Moreover, transition metal-catalyzed ring-expansion reactions and carbonylation processes could also provide straightforward access to ε-lactones.[5] Herein, we report the enantioselective synthesis of tetracyclic indole-fused ε-lactones by the N-heterocyclic carbene (NHC)-Lewis acid catalyzed dynamic kinetic resolution (DKR) of *in situ* generated γ,γ-disubstituted indole 2-carboxaldehydes.[6,7]



Scheme 1 NHC-catalyzed DKR strategies.

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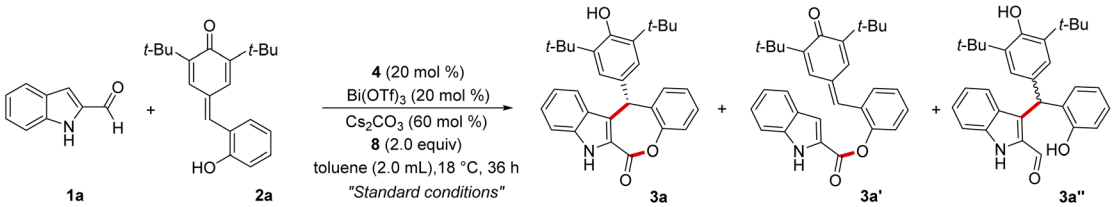
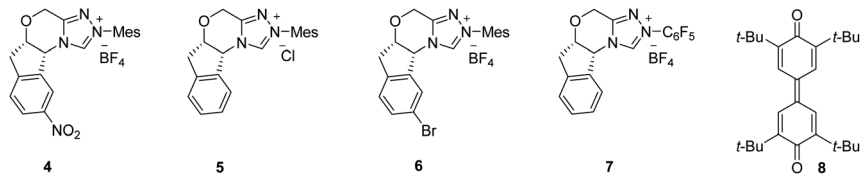
† Electronic supplementary information (ESI) available. Details on experimental procedures, characterization data of all compounds. CCDC 2131951. For ESI and crystallographic data in CIF or other electronic format see https://doi.org/10.1039/d2sc03745a

Table 1 Optimization of the reaction conditions[a]



entry	Variation of the standard conditions[a]	Yield of **3a**[b] (%)	er of **3a**[c]	Yield of **3a′**[b] (%)	Yield of **3a″**[b] (%)
1	None	68	95 : 5	<5	<5
2	**5** Instead of **4**	62	86 : 14	<5	<5
3	**6** Instead of **4**	11	86 : 14	<5	66
4	**7** Instead of **4**	19	81 : 19	<5	<5
5	K_2CO_3 instead of Cs_2CO_3	36	91 : 9	<5	25
6	KO*t*-Bu instead of Cs_2CO_3	<5	-Nd-	<5	<5
7	DABCO instead of Cs_2CO_3	<5	-Nd-	<5	<5
8	THF instead of toluene	<5	-Nd-	71	<5
9	DME instead of toluene	<5	-Nd-	67	<5
10	Mesitylene instead of toluene	22	91 : 9	<5	18
11	$Sc(OTf)_3$ instead of $Bi(OTf)_3$	52	92 : 8	<5	<5
12	CF_3SO_3H instead of $Bi(OTf)_3$	60	91 : 9	<5	<5
13	10 mol% of **4** instead of 20 mol%	31	95 : 5	<5	48
14	1.0 equiv. of **8** instead of 2.0 equiv.	39	94 : 6	<5	28



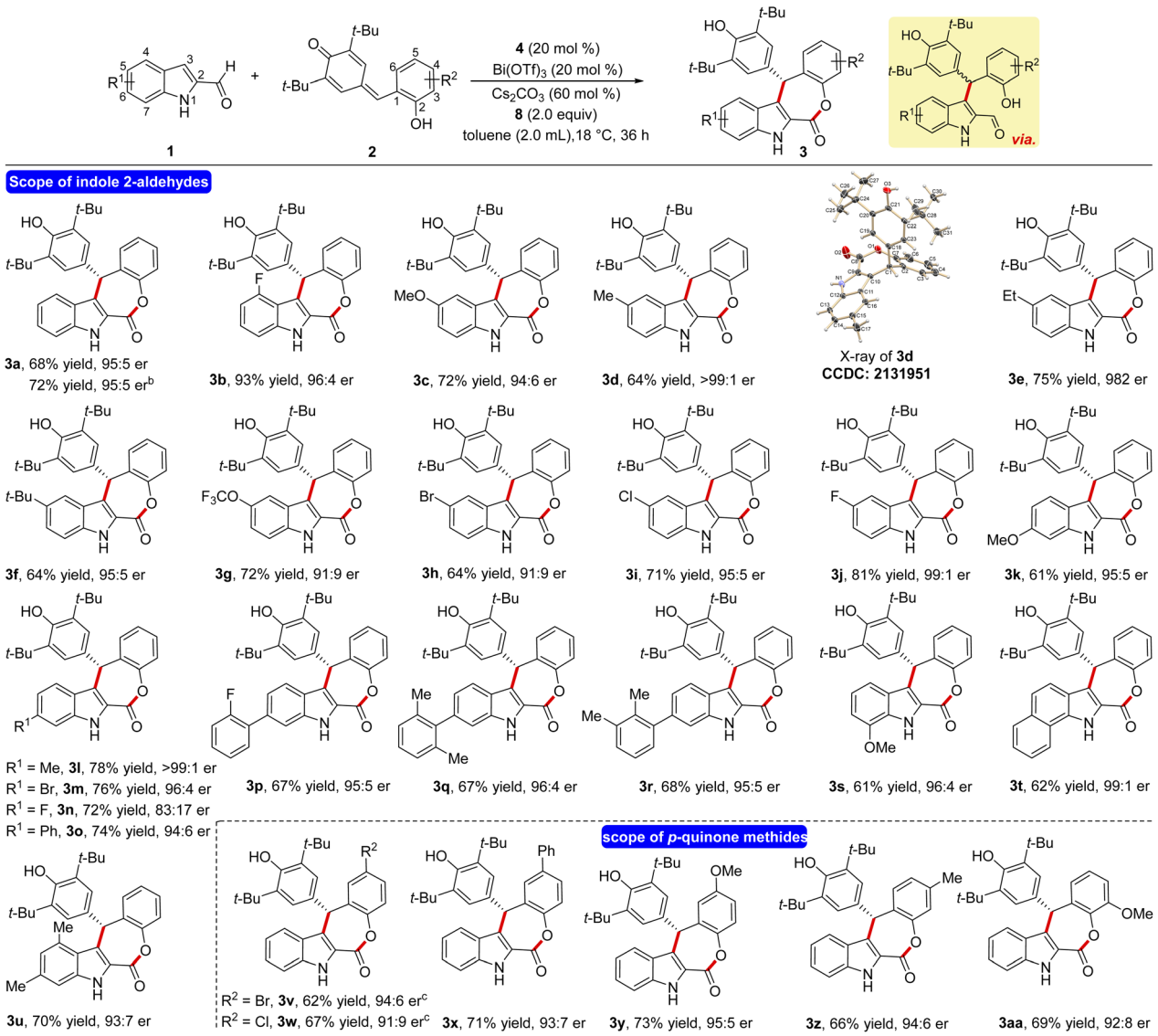
4 5 6 7 8

[a] Standard conditions: **1a** (0.12 mmol), **2a** (0.168 mmol), **4** (20 mol%), $Bi(OTf)_3$ (20 mol%), Cs_2CO_3 (60 mol%), **8** (2.0 equiv.), toluene (2.0 mL), 18 °C and 36 h. [b] Yields of the column chromatography purified products are provided. [c] The er was established by HPLC analysis on a chiral stationary phase.

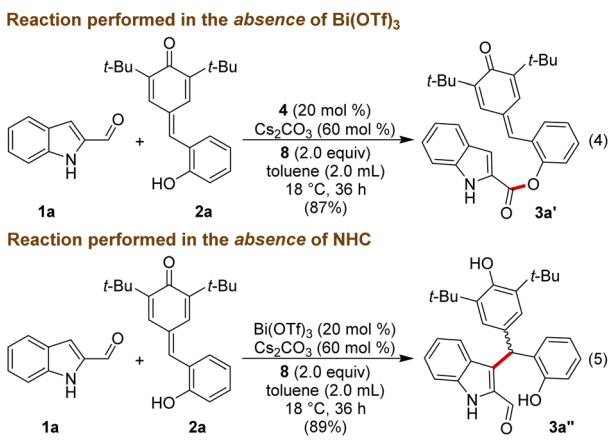
NHC-catalyzed DKR strategies are employed for the conversion of racemic substrates to enantiomerically pure products.[8] Generally, carbene-catalyzed DKR approaches are applicable to racemic carbonyl compounds, where the enantioinduction takes place at the α-carbon centre. For instance, Goodman and Johnson reported the DKR of β-halo α-ketoesters by utilizing the NHC-catalyzed cross-benzoin reaction, where the reaction proceeds *via* the generation of the nucleophilic Breslow intermediate **A** (Scheme 1, eqn (1)).[9–11] Moreover, Chi and co-workers demonstrated the NHC-catalyzed DKR of α-alkyl α-aryl carboxylic esters *via* the transesterification strategy, and the NHC- enolate **B** is the key intermediate (eqn (2)).[12] In all these cases, the α-carbon center is involved in the DKR process, where the generated chiral center is proximal to the reacting center (generation of **D** from **C**), and intriguingly, the synthesis of enantioenriched γ-substituted carboxylic esters from racemic starting materials *via* the DKR process is not known.[13] This will be interesting as the γ-carbon center will be remote from the reacting carbonyl center and enantioinduction will be challenging (conversion of **E** to **F**). In this context, we envisioned the NHC-catalyzed DKR of the γ,γ-disubstituted aldehyde **G** derived from the unprotected indole-2-carboxaldehyde,[14] which can be generated *in situ* by the Lewis acid-catalyzed Friedel–Crafts reaction of indole 2-aldehyde **1a** with the *o*-hydroxyphenyl-substituted *p*-quinone methide **2a**. This formal [4 + 3] annulation reaction afforded indole-fused ε-lactone **3a** in good yields and selectivities. The optimal Lewis acid was $Bi(OTf)_3$, which plays dual roles: (a) in catalyzing the initial Friedel–Crafts reaction generating **G**, and (b) then the involvement in the DKR process for the esterification reaction in cooperation with NHCs.[15] Intriguingly, although NHC-catalyzed DKR strategies are known for the enantioselective synthesis of β-lactones, γ-lactones and δ-lactones, the related DKR strategies for ε-lactones are unknown. It may be noted in this context that NHC-catalyzed synthesis of fused ε-lactones by the [4 + 3] annulation of *o*-quinone methides with enal-derived homoenolates was uncovered independently by Ye's[16] and Scheidt's groups.[17] Moreover, a related NHC-homoenolate route for the synthesis of spirooxindole ε-lactones (without involving the DKR process) is demonstrated by Li's[18a] and Enders' groups.[18b]

Results and discussion

Driven by the idea of inducing stereocontrol at a remote position using the DKR strategy, the present study was initiated by

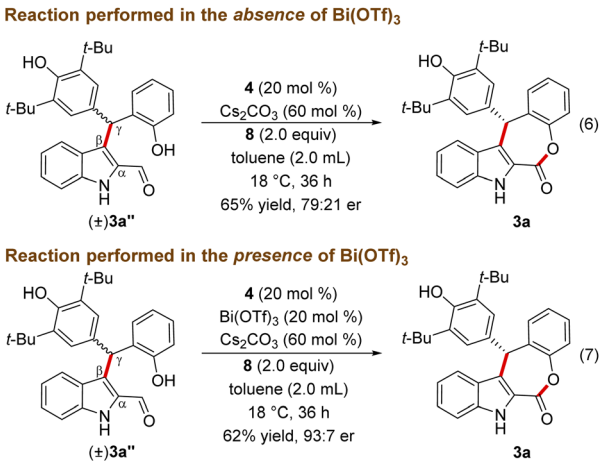


Scheme 2 [a] Reaction conditions: **1** (0.25 mmol), **2** (1.4 equiv.), **4** (20 mol%), $Bi(OTf)_3$ (20 mol%), Cs_2CO_3 (60 mol%), **8** (2.0 equiv.), toluene (4.0 mL), 18 °C and 36 h. Given are isolated yields of the column chromatography purified products. The er was established by HPLC analysis on a chiral stationary phase. [b] The yield and er for a 1.0 mmol scale reaction. [c] The reaction performed at 10 °C for 48 h.



Scheme 3 Control experiments.

treating indole 2-carboxaldehyde **1a** with the *p*-quinone methide **2a** in the presence of NHC generated from the chiral triazolium salt **4** using Cs_2CO_3 as the base under oxidative conditions using the bisquinone **8**. Interestingly, under these conditions, the desired indole-fused ε-lactone **3a** was formed in 68% yield and a 95 : 5 enantiomeric ratio (er) (Table 1, entry 1). The product **3a** was formed by the initial Friedel–Crafts reaction of **1a** with **2a** catalyzed by $Bi(OTf)_3$ (generating *in situ* **3a''**), followed by the NHC/Lewis acid-catalyzed DKR *via* a stereoselective esterification reaction. Notably, the ester **3a′** (formed by the esterification of **1a** with the phenol moiety of **2a**),[19] and the Friedel–Crafts product **3a″** were not isolated under these conditions. Moreover, compared to the carbene formed from **4**, other chiral triazolium salts **5–7** provided less yield and selectivity of **3a** (entries 2–4). The screening of other bases and solvents revealed that Cs_2CO_3 is the optimal base and toluene is



Scheme 4 Role of a Lewis acid in the DKR process.

the best solvent for this transformation (entries 5–10). The use of $Sc(OTf)_3$ as the Lewis acid and CF_3SO_3H as the Brønsted acid for initiating the Friedel–Crafts reaction was also not efficient (entries 11 and 12). In addition, performing the reaction with 10 mol% of **4** or using 1.0 equiv. of **8** resulted in an incomplete reaction with the isolation of the Friedel–Crafts adduct **3a**″ maintaining high selectivity (entries 13,14). Hence, entry 1 was selected as the best condition for the substrate scope analysis.[20]

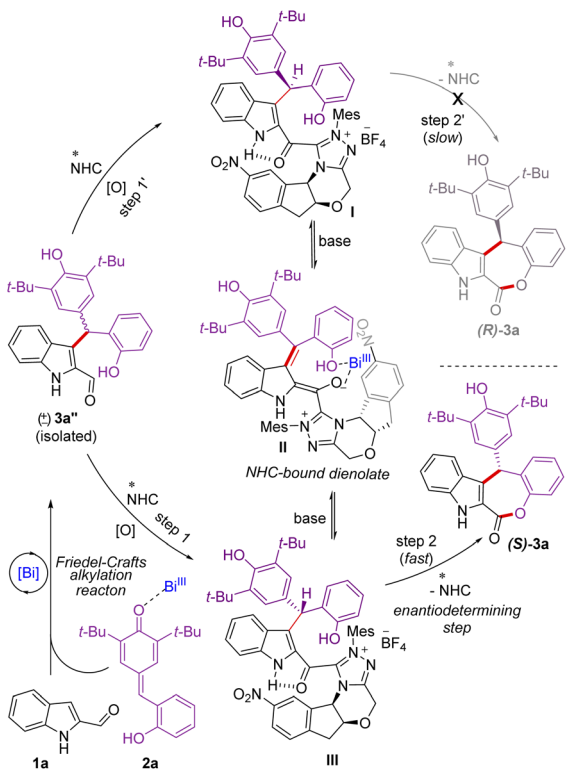
Having the optimized reaction conditions in hand, the scope and limitations of the present NHC-catalyzed DKR has been examined. First, the variation of the indole 2-carboxaldehyde has been studied. The unsubstituted parent aldehyde worked well and 4-fluoro substituted aldehyde furnished the tetracyclic ε-lactone **3b** in 93% yield and 96 : 4 er (Scheme 2). The formation of **3a** in 72% yield and 95 : 5 er on a 1.0 mmol scale indicates that the present DKR process is scalable and practical. A variety of electronically different substituents at the 5-position of indole 2-carboxaldehyde was well tolerated under the optimized conditions and the corresponding ε-lactones were formed in good yields and selectivities (**3c–3j**). In the case of the methyl derivative **3d**, the structure and the absolute stereochemistry of the chiral center were confirmed using X-ray analysis of the crystals.[21] Moreover, substrates bearing different groups at the 6-position of indole 2-carboxaldehye underwent a smooth NHC-catalyzed annulation reaction to afford the desired products in good yields and er values (**3k–3r**). In addition, the reaction using 7-methoxy indole 2-carboxaldehyde furnished the product **3s** in 61% yield and 96 : 4 er. Furthermore, disubstituted indole -aldehydes also provided good yield of the target product thus expanding the scope of this annulation (**3t** and **3u**).

Next, the variation in the *o*-hydroxyphenyl-substituted *p*-quinone methide moiety was studied. The *p*-quinone methides having –Br, –Cl, Ph and –OMe groups at the 5-position are well tolerated under the present conditions and the desired annulated products are formed in reasonable yields and selectivities (**3v–3y**). Moreover, –Me and –OMe groups at the 4- and 3-position of **2** did not affect the reaction outcome and the target ε-lactones are formed in good yields and er values (**3z** and **3aa**).

To get insight into the mechanism of the reaction, a few mechanistic experiments were performed. When the reaction of **1a** was performed with **2a** in the absence of $Bi(OTf)_3$, the reaction furnished the ester product **3a**′ in 87% yield, and **3a** was not formed under these conditions (Scheme 3, eqn (4)). Notably, related esterification reactions catalyzed by NHCs are reported by Studer and co-workers.[19] Moreover, treatment of **1a** with **2a** in the absence of NHC resulted in the formation of the Friedel–Crafts adduct **3a**″ in 89% yield (eqn (5)).

The lack of the desired product **3a** formation in the absence of either $Bi(OTf)_3$ or NHC indicates the role of these two catalysts for the direct and enantioselective synthesis of the ε-lactone **3a**. To get further insight into the role of $Bi(OTf)_3$ in the DKR process, the Friedel–Crafts alkylation product **3a**″ was treated with NHC generated from **4** under oxidative conditions in the absence of $Bi(OTf)_3$. This reaction afforded **3a** in 65% yield and 79 : 21 er (Scheme 4, eqn (6)). Interestingly, when the same reaction was conducted in the presence of $Bi(OTf)_3$ the product **3a** was formed in 62% yield and an improved er of 93 : 7 shedding light on the role of a Lewis acid in the DKR process (eqn (7)).[22] It is reasonable to assume that the Bi(III) Lewis acid is involved in coordination with the NHC-bound dienolate and the phenolic –OH moiety for the facile dienolate protonation and intramolecular acylation.[23,24]

Mechanistically, in the presence of Lewis acidic $Bi(OTf)_3$, indole 2-carboxaldehyde **1a**[25] adds to the *p*-quinone methide **2a** generating *in situ* the racemic γ,γ-disubstituted indole 2-carboxaldehyde **3a**″ through an intermolecular Friedel–Crafts alkylation reaction (Scheme 5). Under oxidative conditions, the



Scheme 5 Proposed mechanism of the reaction.

addition of NHC to the aldehyde **3a**″ could generate the diastereomeric NHC-bound acylazoliums **I** and **III**.[26] It is reasonable to assume that the NHC acylazolium **I** could not undergo intramolecular acylation due to the presence of a bulky chiral indanone core of the catalyst. Hence, the formation of (***R***)-**3a** is not feasible. On the other hand, the NHC acylazolium **III** undergoes facile intramolecular acylation to afford the desired product (***S***)-**3a** as the aminoindanol and the bulky 2,6-di-*tert*-butyl phenolic moieties are on the opposite side. The acylazolium **I** under basic conditions could form the NHC-dienolate intermediate **II**,[6j,27] which could undergo enantioselective protonation to generate the intermediate **III**, which can further undergo acylation to form the product (***S***)-**3a**. During the re-protonation of NHC-bound dienolate intermediate **II**, $Bi(OTf)_3$ is likely involved in the coordination with the dienolate and –OH moieties to facilitate protonation and then esterification.

In conclusion, we have presented the NHC-Lewis acid cooperative catalyzed DKR for the enantioselective synthesis of tetracyclic indole-fused ε-lactones, a formal [4 + 3] annulation. The transiently generated γ,γ-disubstituted indole 2-carboxaldehydes from indole-2-carboxaldehyde and 2-hydroxy phenyl *p*-quinone methides using $Bi(OTf)_3$ catalysis underwent an efficient DKR process, where the NHC-bound dienolates are the key intermediates. In the presence of NHC and $Bi(OTf)_3$, facile ε-lactonization takes place with enantioinduction at the γ-position. The tetracyclic ε-lactones are formed in up to 93% yield and >99 : 1 er. The stereoinduction at the remote γ-carbon, mild reaction conditions, and *in situ* generation of the racemic substrate for DKR are the notable features of the present annulation reaction.

Data availability

Details of the experimental procedures, mechanistic experiments, characterization data of all the tetracyclic indole-fused ε-lactones, and X-ray data of **3d**.

Author contributions

K. B. and A. T. B. conceived and designed the project. K. B. performed the optimization studies, substrate scope analysis and mechanistic studies. S. B. and S. S. helped in the substrate scope studies. R. G. G. performed the X-ray crystallographic analysis. K. B. and A. T. B. wrote the manuscript. All authors have given approval to the final version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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23 Performing the reaction of **3a'** under the optimized conditions to check the feasibility of intramolecular cyclization leading to **3a** did not work indicating that Friedel-Crafts alkylation proceeds prior to annulation.

24 To get insight into the DKR process, the reaction of **3a″** was performed under the optimized conditions for 12 h and the ee of the recovered **3a″** was determined. Detection of **3a″** in the racemic form is an indication that the present reaction is proceeding *via* DKR.

25 Presently, this annulation works with indole 2-carboxaldehydes as nucleophiles, and the attempted reactions with other aldehydes such as pyrrole 2-carboxaldehyde, benzofuran 2-carboxaldehyde and 3,4,5-trimethoxy benzaldehyde as nucleophiles did not afford the desired annulation products under the optimized conditions.

26 The reaction of N-methyl indole-2-carbaldehyde instead of 1a under the optimized reaction conditions afforded N-methyl ε-lactones in 93% yield and 50:50 er. This result indicates that free N-H required for getting selectivity, and the N-H group is possibly involved in H-bonding with the acylazolium moiety.

27 X. Chen, S. Yang, B. A. Song and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2013, **52**, 11134.