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A tandem dearomatization/rearomatization strategy: enantioselective N-heterocyclic carbene-catalyzed α-arylation†

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In this study, the first example of the carbene-catalyzed tandem dearomatization/rearomatization reaction of azonaphthalenes with α-chloroaldehydes is described. This protocol enables the efficient assembly of chiral dihydrocinnolinone derivatives in good yields with excellent enantioselectivities (up to 99% ee). Moreover, this strategy enables not only the highly enantioselective NHC-catalyzed nucleophilic aromatic substitution, but also a formal Csp^2–Csp^3 bond formation.

Advances in reaction development for the stereoselective construction of medicinally important scaffolds or high value-added chemicals depend on utilizing innovative and long-standing synthesis strategies.[1] Over the past decade, a large number of organic transformations driven by N-heterocyclic carbene (NHC) catalysis have been rapidly developed that enabled certain types of reaction manifolds and asymmetric versions of important compounds.[2] Since the seminar report of the Breslow intermediate in 1958, there has been an ever-increasing demand in recruiting novel NHC-bound intermediates for their applications in organic synthesis.[3] Among these achievements, the exploration of NHC-bound enolates for new bond formations has attracted considerable attention from the synthetic community due to its high chemical reactivity and remarkable stereo-control. As shown in Fig. 1a, several readily available starting materials (*e.g.*, enals, aldehydes, ketenes, carboxylic acids, esters) have proven to be effective reactants for the *in situ* generation of azolium enolates, thus resulting in a large number of distinct reactions and diversified core skeletons. In 2006, Bode *et al.* first reported an elegant example of the protonation of electron-deficient enals to produce azolium enolates and the subsequent trapping by *N*-sulfonyl, α,β-unsaturated imines to yield dihydropyridinones.[4] Rovis *et al.* have pioneered in using α-chloroaldehydes as reactants to prepare azolium enolates for further protonation[5a] or internal redox reaction.[5b] Meanwhile, Smith *et al.* also confirmed that α-aroyloxyaldehydes as precursors could convert to azolium enolates in NHC-catalyzed redox esterification, amination, and cycloaddition reactions.[6] Moreover, the Smith *et al.*[7a] and Ye

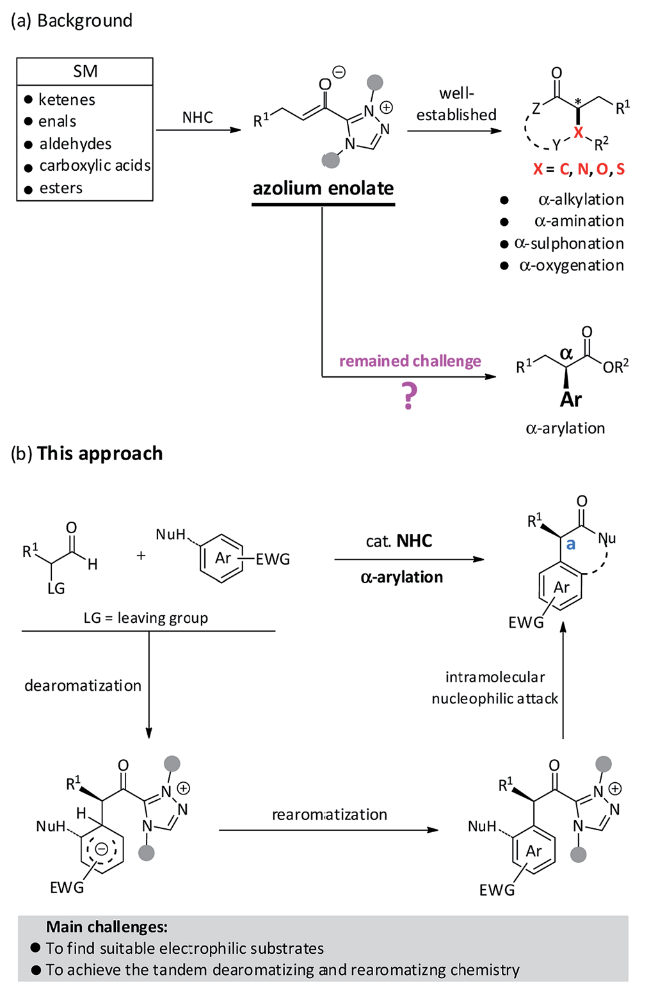

Fig. 1 Representative transformations of azolium enolates catalyzed by NHCs.

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et al.[7b,c] have documented that azolium enolates could be readily prepared from ketenes for further annulation. Rovis *et al.*, Chi *et al.*, Scheidt *et al.*, and Ye *et al.* have utilized aliphatic aldehydes,[8a] activated esters,[8b] carboxylic acids[8c,d] and anhydrides[8e] as suitable reactants to successfully achieve azolium enolates, respectively. In brief, the synthetic utilities of azolium enolates have widely extended to various [2 + 2],[7a–c,9] [2 + 2 + 2],[9f,10] [3 + 2][11] and [4 + 2][4,6,7c,8a–c,12] cycloadditions. These broad diversities may be attributed to the special property of absence of polarity reversal of azolium enolates. Nonetheless, NHC-catalyzed α-arylation still remains a formidable challenge for synthetic chemists.

Given the success of *in situ* generated azolium enolates, we anticipated that the desirable NHC-catalyzed α-arylation reaction might partially be attributed to the recruiting of suitable substrates. In 2015, Glorius *et al.* found that the NHC-bound enolates could react with aromatic azomethine imines to generate pyrazolo[5,1-*a*]isoquinolines *via* a direct dearomatization process.[13] Inspired by this prominent result, we speculated that a matching electrophile (*e.g.*, electron-deficient aromatic compound) may facilitate the initial dearomatization step *via* a nucleophilic attack and C–C bond formation, followed by a rearomatization process, if successfully, to offer the desired α-arylated molecules (Fig. 1b). We also envisioned that the thermodynamics of this intramolecular cycloaddition process probably helps to drive the nucleophilic dearomatization step.

In the process of recruiting suitable substrates, we particularly focused on the azobenzene scaffolds because it has the basic required characteristics of being the matching substrate. First, the azobenzene-type structures can be used as electrophiles in the critical addition step. Second, the azo group can assist in accomplishing the tandem dearomatization–rearomatization process *via* intermolecular tautomerization. In fact, azobenzene derivatives as synthons have been broadly utilized in metal-catalyzed transformations, as illustrated by rhodium-catalyzed [3 + 2] cyclization of electron-deficient alkenes with azobenzenes[14] (Fig. 2a). Until recently, the Tan *et al.*[15] reported an elegant example of chiral phosphoric acid-catalyzed [3 + 2] cyclization of azonaphthalenes with 2,3-disubstituted indoles (Fig. 2b). In these successful examples, the azo motif within the azonaphthalenes not only works as an electron-withdrawing group to activate the aromatic ring, but also plays a critical role in triggering the rearomatization process. Meanwhile, the NHC-bounded homoenolates, azolium enolates or acyl anions have proven to be effective nucleophiles in catalytic nucleophilic dearomatization.[13,16] Inspired by these achievements,[15,17] we then set out to explore the feasibility of NHC-catalyzed nucleophilic dearomatization of azonaphthalenes with α-chloroaldehyde. Unambiguously, the following challenges need to be overcome in this design: (1) controlling the regioselectivity as the nucleophilic addition of azobenzene derivatives can probably occur at either the N═N double bond[7c,12h,i,18] or the aromatic ring. (2) Check the compatibility of reactive azonaphthalenes with the nucleophilic NHC-bounded enolate intermediates in the dearomatization reaction. (3) Identify the efficient catalytic system for achieving high enantioselectivity. Herein, we report an unprecedented example of NHC-catalyzed

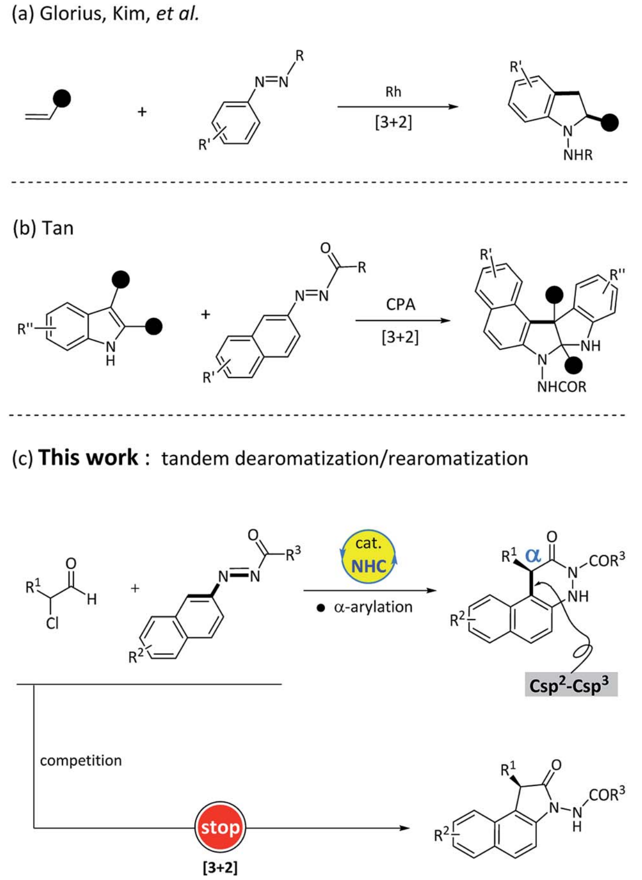


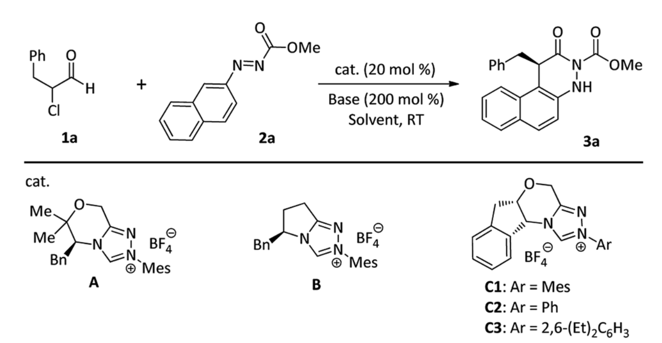
Fig. 2 Anticipated cyclization reactions of azobenzene molecules.

α-arylation of azonaphthalenes with α-chloroaldehydes. It should be mentioned that this process contains a formal Csp^2–Csp^3 bond formation and starts from an organocatalytic nucleophilic aromatic substitution (Fig. 2c).

To validate the feasibility of the hypothesis, our initial reaction development was conducted with α-chloroaldehyde (**1a**) and azonaphthalene (**2a**) in the presence of 20 mol% NHC precatalysts and DIPEA in THF at room temperature (Table 1). Only a trace amount or a moderate yield of **3a** was achieved using NHC precatalyst **A** or **B** (entries 1 and 2). Gratifyingly, the *N*-Ph-substituted chiral triazolium catalyst (**C2**) afforded **3a** in 73% yield with 90% ee (Table 1, entry 4). Further investigation indicated that the *N*-2,4,6-$(Me)_3C_6H_2$- or *N*-2,6-$(Et)_2C_6H_3$-substituted chiral triazolium catalyst **C1** or **C3** gave excellent enantioselectivities, but tolerated moderate yields (entries 3 and 5). Further fine-tuning of other parameters (*e.g.*, base, solvent, and catalyst loading, see ESI† for more details) revealed that the optimal condition is a combination of room temperature, 10 mol% **C1**, 200 mol% DIPEA, and 1.0 mL of ^{t}BuOMe (Table 1, entry 19).

After establishing the optimal reaction conditions, we examined the substrate scope with respect to various α-chloroaldehydes **1** (Fig. 3). The reaction was applicable to α-chloroaldehyde derivatives with either aromatic rings or alkyl chains. The electronic natures or substituted patterns on the aromatic

Table 1 Optimization[a]



Entry	Cat.	Solvent	Base	Yield[b] (%)	ee[c] (%)
1	**A**	THF	DIPEA	8	—
2	**B**	THF	DIPEA	58	88
3	**C1**	THF	DIPEA	76	99
4	**C2**	THF	DIPEA	73	90
5	**C3**	THF	DIPEA	71	99
6	**C1**	THF	DBU	Trace	—
7	**C1**	THF	Cs_2CO_3	22	24
8	**C1**	DCM	DIPEA	77	97
9	**C1**	^{t}BuOMe	DIPEA	90	99
10	**C1**	CH_3CN	DIPEA	71	82
11[d]	**C1**	^{t}BuOMe	DIPEA	89	99
12[e]	**C1**	^{t}BuOMe	DIPEA	61	99

[a] Reaction conditions: α-chloroaldehyde **1a** (0.20 mmol, 2.0 equiv.), azonaphthalene **2a** (0.10 mmol, 1.0 equiv.), cat. (0.02 mmol), base (0.20 mmol), solvent (1.0 mL), 10 h, room temperature. [b] Yields of isolated products after column chromatography. [c] The ee values were determined by HPLC using a chiral stationary phase. [d] **C1** (10 mol%), 16 h. [e] **C1** (5 mol%), 24 h.

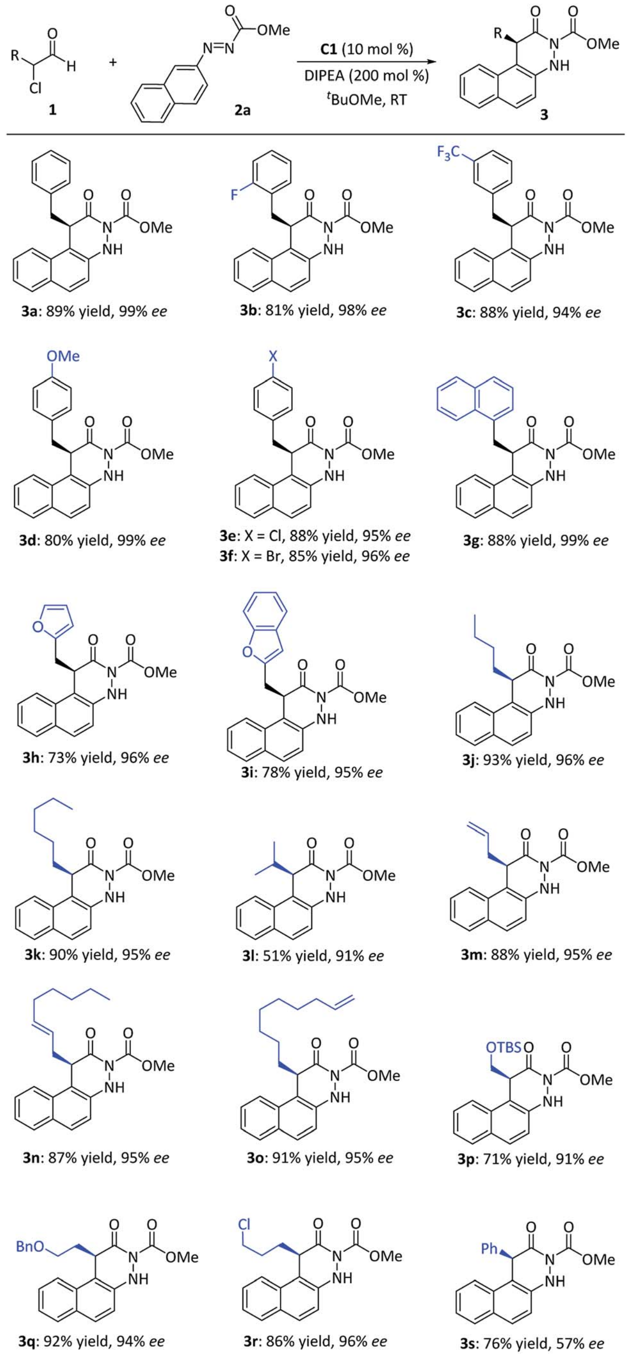


Fig. 3 Scope of α-chloroaldehydes. [a]Reaction conditions: **1** (0.20 mmol), **2a** (0.10 mmol), cat. **C1** (10 mol%), DIPEA (0.20 mmol), ^{t}BuOMe (1.0 mL), 12–16 h, room temperature.

ring appeared to have limited effects on reaction results, affording the corresponding dihydrocinnolines in yields of 73–88% and ee values between 94 and 99% (**3a–3i**). When the aldehydes containing alkyl R-substituents located at the α-carbon were used, the corresponding dihydrocinnoline derivatives were also afforded with good yields and excellent enantiocontrols (**3j–3l**). Notably, when α-chloroaldehydes bore functional alkyl subunits (*e.g.*, alkene, chlorine, ether) at the side chain, good yields with excellent enantioselectivities were also regularly observed (**3m–3r**). Pleasingly, 2-chloro-2-phenylacetaldehyde also delivered the corresponding product (**3s**) in a moderate yield, albeit with a relatively low ee value.

Further investigation on the synthetic feasibility of azonaphthalenes (**2**) was performed with α-chloroaldehyde (**1a**), as shown in Fig. 4. The results indicated that this reaction tolerated a diverse array of azonaphthalenes, and afforded the dihydrocinnolines (**4**) in good to high yields (76–93%) and with high levels of enantio-controls (93–99% ee). When R′ substituents were alkyl oxide groups (**4a–4d**), amino group (**4e**) or sulfonyl group (**4f**), the products were obtained in high yields with excellent enantioselectivities. Specifically, the electronic nature or the substitution pattern of the aromatic rings showed limited effects on the reactivity (**4g–4l**). When an anthracene moiety replaced the naphthalene ring in azonaphthalenes, 76% yield and 95% ee were still achieved (**4m**). The absolute configuration of **3r** was determined by single-crystal X-ray diffraction analysis,[19] and those of other products were assigned by analogy.

Furthermore, to demonstrate the practicality of this catalytic transformation, a gram-scale synthesis of **3a** was conducted under the optimal condition. There was almost no change in the reaction yield and enantioselectivity (Fig. 5, eqn (1), 90%, 97% ee), implying that the catalytic tandem reaction of

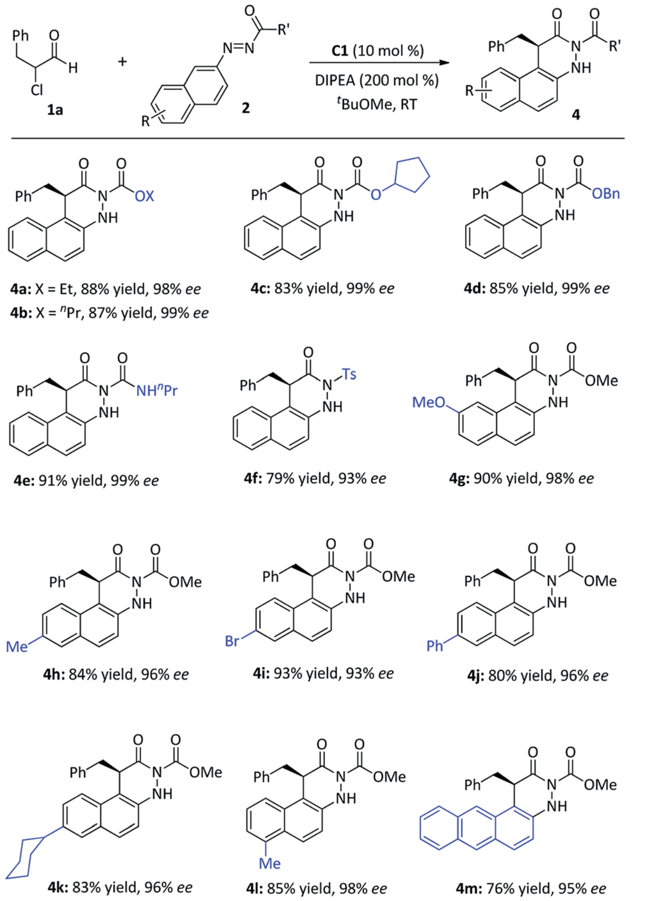


Fig. 4 Scope of azonaphthalenes. [a]Reaction conditions: **1a** (0.20 mmol), **2** (0.10 mmol), cat. **C1** (10 mol%), DIPEA (0.20 mmol), ^{t}BuOMe (1.0 mL), 16 h, room temperature.

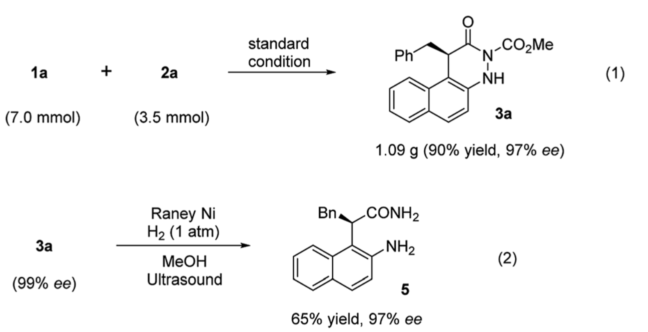
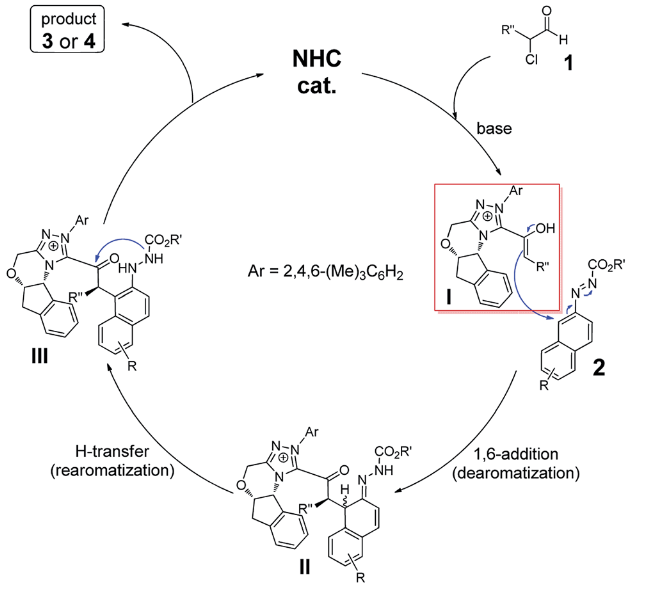


Fig. 5 Scale-up synthesis and further transformation.

azonaphthalenes with α-chloroaldehydes can be scaled up. Moreover, the mediated cleavage of **3a** mediated by RANEY®-Ni led to the formation of α-substituted chiral amide (**5**) in 65% yield with the same ee value (Fig. 5, eqn (2)).

As illustrated in Scheme 1, a postulated mechanism is described. Initial addition of catalyst **C1** to α-chloroaldehyde **1** followed by 1,2-H migration generates NHC-bounded enolate **I**. Nucleophilic addition of enolate **I** to azonaphthalene (**2**) results in a formal tandem reaction of dearomatization[13,16] and



Scheme 1 Proposed mechanism.

rearomatization along with C–H cleavage and N–H formation to give the thermodynamically stable intermediate **III**. Finally, intramolecular *N*-acylation of **III** leads to the final product **3** or **4** and the NHC catalyst **C1** is released for the next catalytic cycle. Surely, a concerted [4 + 2] annulation mechanism cannot be completely ruled out in this case.

In summary, a novel NHC-catalyzed tandem dearomatization/rearomatization reaction of azonaphthalenes with α-chloroaldehydes has been developed.[20] This protocol allows for the rapid assembly of the dihydrocinnolinone scaffolds in good to high yields with high to excellent enantioselectivities. Further investigations on the construction of other relevant frameworks as well as a detailed mechanistic study are currently underway in our laboratory.

Conflicts of interest

There are no conflicts to declare.

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