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Intramolecular Csp<sup>3</sup>–H/C–C bond amination of alkyl azides for the selective synthesis of cyclic imines and tertiary amines†Xiaojin Wen,<sup>‡a</sup> Xinyao Li,<sup>‡a</sup> Xiao Luo,<sup>a</sup> Weijin Wang,<sup>a</sup> Song Song<sup>ID</sup><sup>\*ab</sup> and Ning Jiao<sup>ID</sup><sup>\*a</sup>

The intramolecular Csp<sup>3</sup>–H and/or C–C bond amination is very important in modern organic synthesis due to its efficiency in the construction of diversified N-heterocycles. Herein, we report a novel intramolecular cyclization of alkyl azides for the synthesis of cyclic imines and tertiary amines through selective Csp<sup>3</sup>–H and/or C–C bond cleavage. Two C–N single bonds or a C=N double bond are efficiently constructed in these transformations. The carbocation mechanism differs from the reported metal nitrene intermediates and therefore enables metal-free and new transformation.

## Introduction

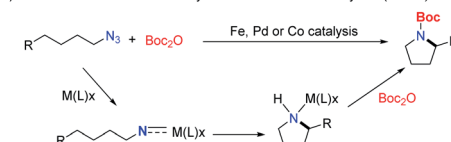
N-Heterocycles are undoubtedly important chemicals in organic synthesis, and have been considered as key functionality regulators in pharmaceuticals.<sup>1</sup> The intramolecular nitrogen insertion into Csp<sup>3</sup>–H and/or C–C bonds provides an efficient approach to N-heterocycles.<sup>2–5</sup> The pioneering groups of Aubé<sup>4</sup> and Pearson<sup>5</sup> developed the intramolecular Schmidt reactions<sup>2</sup> and made significant achievements for various N-heterocycle synthesis.<sup>3</sup> The earliest intramolecular aliphatic C–N bond formation named the Hofmann–Löffler–Freitag reaction<sup>5</sup> always started from unstable halogenated amines to construct N-heterocycles. Over the past two decades, the aliphatic C–H amination has achieved great progress *via* the C–H activation strategy.<sup>6</sup> However, most of these reactions required electron withdrawing directing groups and delivered amide products (Scheme 1a). Beginning with Breslow's pioneering work,<sup>7</sup> a metal-nitrene strategy was successfully applied in intramolecular Csp<sup>3</sup>–H bond N insertion, providing elegant approaches to amides bearing N–H bonds (Scheme 1a).<sup>8</sup> Thus, the development of direct aliphatic C–H/C–C amination is still highly desirable.

Organic azides are synthetically useful in drug discovery, bioconjugation and materials science.<sup>9</sup> Although the intramolecular Csp<sup>3</sup>–H bond amination/amidation of aryl azides<sup>10</sup>

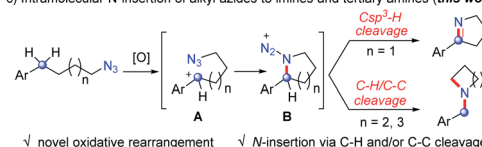
and sulfonyl azides<sup>11</sup> has achieved great progress, the corresponding transformation of alkyl azides<sup>12</sup> was rarely developed until recent results.<sup>13</sup> In 2013, Betley and coworkers demonstrated the pioneering intramolecular aliphatic C–H amination of alkyl azides catalyzed by an iron catalyst (Scheme 1b).<sup>13a</sup> The groups of van der Vlugt,<sup>13c</sup> Lin,<sup>13d,e</sup> de Bruin,<sup>13c,f</sup> and Chi<sup>13g</sup> independently developed the same elegant intramolecular cyclization of alkyl azides by iron, palladium or cobalt catalysis to deliver N-Boc heterocycles (Scheme 1b), in which the involved nitrene type intermediates required an equivalent of Boc<sub>2</sub>O reagent to liberate the active catalyst to complete the catalytic cycle (Scheme 1b). Despite the advances of the above strategies (Scheme 1a and b), these intramolecular aliphatic amination/amidation processes always delivered N-carbonyl or sulfonyl heterocycles with the formation of one C–N single bond.

a) Intramolecular Csp<sup>3</sup>–H bond amination/amidation by C–H activation and nitrene strategies

b) Intramolecular amination of alkyl azides to N-Boc heterocycles (ref. 13)



c) Intramolecular N-insertion of alkyl azides to imines and tertiary amines (this work)

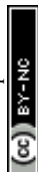
Scheme 1 Intramolecular N-insertion of the Csp<sup>3</sup>–H bond.

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Scheme 2 Proposed mechanism.



On the basis of this result, we investigated the one-pot reaction of alkyl azide **3** with DDQ and TFA followed by *in situ* reduction. We were delighted to find that the corresponding cyclic tertiary amine **7a** was obtained in 55% yield (Table 3). The substituent on the arene slightly influenced the yield and

a series of N-Bn pyrrolidines were synthesized in moderate yields. The azide substrates bearing alkyl substituents also smoothly delivered benzyl-substituted **7h** or pyrrolidine **7i** in moderate yield. In addition, naphthalene, thiophene, dibenzofuran and dibenzothiophene were all well tolerated to afford cyclic tertiary amines **7j–m** in 33–81% yields. It is noteworthy that the transformation of **3** to **7** with the release of nitrogen as the only by-product, is thus highly atom-economic. Moreover, the present strategy cleaves the Csp<sup>3</sup>–Csp<sup>3</sup> bond<sup>16</sup> without strained rings or assisted functional groups. Besides pyrrolidine, piperidine derivative **7n** also could be synthesized by the intramolecular N-insertion of alkyl azide **3n**. Unfortunately, the present strategy could not be applied in the construction of seven- or eight-membered N-heterocycles.

Based on the above experiments, we proposed the possible mechanism of the reaction (Scheme 2). The oxidation of alkyl azides **1** and **3** at the benzylic position by DDQ with TFA provides benzylic cation intermediate **A**, which is attacked by the azide group to generate cyclic intermediate **B**. In the most stable conformation of **B**, the aryl group should stand on the equatorial bond, which makes a small torsion angle with the azide moiety. As a result, the following Schmidt rearrangement of **B** with the concerted release of N<sub>2</sub> and the aryl shift is unfavorable through periplanar migration, while the hydrogen or alkyl shift is potentially feasible through antiperiplanar migration. The five-membered ring species **C** undergoes deprotonation with the release of N<sub>2</sub> to afford cyclic imine **2**,

Scheme 3 Energy profile for the DDQ-mediated amination of alkyl azides **1** and **3**.Table 3 Nitrogenation of alkyl azides to tertiary amines<sup>a</sup>

<sup>a</sup> Reaction conditions: **3** (0.3 mmol), DDQ (0.36 mmol) and TFA (0.2 mL) in TCE (0.5 mL) at room temperature for 12 h. Isolated yields. <sup>b</sup> Performed with TFA (0.4 mL) at 60 °C. <sup>c</sup> Performed at 60 °C.



while the six-membered ring intermediate **D** undergoes 1,2-alkyl migration to generate the imine cation **E**, which is sequentially reduced to deliver tertiary amine **7**.

To further understand the mechanism, we performed preliminary DFT calculations on the model reaction of alkyl azides **1** and **3** with DDQ and TFA (Scheme 3).<sup>17</sup> We first studied the oxidation of **1** at the benzylic position by DDQ with TFA through O-attack hydride transfer pathway, which is the most thermodynamically favorable pathway in some similar cases.<sup>18</sup> The hydride transfer from **1** to the complex of DDQ and TFA through **TS1** requires a Gibbs free energy barrier of 28.0 kcal mol<sup>-1</sup> to form the benzylic carbocation intermediate **A1** and DDQH-TFA<sup>-</sup> anion, which could be stabilized by another TFA molecule to afford DDQ-2H and H(CF<sub>3</sub>CO<sub>2</sub>)<sub>2</sub><sup>-</sup> species. Subsequently, the azide moiety would attack the formed carbocation in **A1** to generate five-membered ring **C**, which is exothermic by 19.2 kcal mol<sup>-1</sup>. In the most stable conformation of **C**, the phenyl group on the equatorial bond has a small torsion angle (-24.4°) with the azide moiety, while the benzylic hydrogen and alkyl group have big dihedral angles (95.4° and -150.0°, respectively) with the azide moiety. Therefore, the following Schmidt rearrangement<sup>2</sup> of **C** with the concerted release of N<sub>2</sub> and the hydrogen or alkyl shift is potentially feasible through antiperiplanar migration. The Schmidt rearrangement with the 1,2-H shift through the antiperiplanar transition state **TS2** with a free energy barrier of 16.8 kcal mol<sup>-1</sup> gives **2-H**. The barrier of the 1,2-alkyl shift to imine cation **E1** through **TS3** ( $\Delta G^\ddagger = 21.7$  kcal mol<sup>-1</sup>) is much higher than that of the 1,2-H shift pathway.

Alternatively, the hydride transfer from **3** to the complex of DDQ and TFA through **TS4** requires a Gibbs free energy barrier of 26.6 kcal mol<sup>-1</sup> to form the benzylic carbocation **A3**. The azide moiety is favorable to attack the intramolecular carbocation to generate six-membered ring **D**, which is exothermic by 16.6 kcal mol<sup>-1</sup>. In the most stable conformation of **D**, the dihedral angle of the azide moiety with the alkyl group increases to -159.5°, while the one with hydrogen decreases to 84.2°. This is likely to provide an advantage for the 1,2-alkyl shift. The following Schmidt rearrangement of **D** including the 1,2-H shift through **TS5** requires a free energy barrier of 15.3 kcal mol<sup>-1</sup> to give **4-H**. In contrast with **C**, **D** undergoes a 1,2-alkyl shift through **TS6** with a free energy barrier of 14.4 kcal mol<sup>-1</sup>, which is favorable compared to the 1,2-H shift pathway, indicating that the 1,2-alkyl shift pathway becomes predominant. Reviewing the whole energy profile, it is revealed that the oxidation with hydride transfer is the rate-determining step, while the chemoselectivity in the nitrogenation of alkyl azides is essentially controlled by the conformation of the cyclic intermediate and the ring-side in the Schmidt rearrangement process. The experimentally observed electronic effects on the Ar group are consistent with the first oxidation step with hydride transfer as the rate-determining step (see the ESI† for details).

## Conclusions

In summary, we have demonstrated a novel metal-free intramolecular Csp<sup>3</sup>-H/C-C amination of alkyl azides for the

synthesis of cyclic imines and tertiary amines. Two C-N single bonds or a C=N double bond are efficiently constructed in these transformations through the highly selective benzyl Csp<sup>3</sup>-H or C-C bond cleavage. The mechanistic studies and DFT calculation indicate a carbocation pathway for this novel protocol. The present chemistry not only provides a new approach to N-heterocycles, but also expands the transformation and application of C-H/C-C amination in organic synthesis.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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- 17 All of the geometry optimizations and frequency calculations were performed with the M06-2X functional implemented in Gaussian 09. All of the energies discussed in the paper are Gibbs free energies at the def2-TZVP basis set based on the structures with the PCM solvation correction in DCE at the 6-31+G(d,p) basis set. Computational details and references are given in the ESI.†
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