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Chemodivergent synthesis of *N*-(pyridin-2-yl) amides and 3-bromoimidazo[1,2-*a*]pyridines from α-bromoketones and 2-aminopyridines†

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N-(Pyridin-2-yl)amides and 3-bromoimidazo[1,2-*a*]pyridines were synthesized respectively from α-bromoketones and 2-aminopyridine under different reaction conditions. *N*-(Pyridin-2-yl)amides were formed in toluene *via* C–C bond cleavage promoted by I_2 and TBHP and the reaction conditions were mild and metal-free. Whereas 3-bromoimidazopyridines were obtained in ethyl acetate *via* one-pot tandem cyclization/bromination when only TBHP was added, the cyclization to form imidazopyridines was promoted by the further bromination, no base was needed, and the versatile 3-bromoimidazopyridines could be further transferred to other skeletons.

Introduction

Aminopyridines serve as pharmacophores for many molecules with significant biological and therapeutic value.[1] Particularly, *N*-(pyridin-2-yl)amides[2] and imidazo[1,2-*a*]pyridines[3] have received great attention in recent years due to their varied medicinal applications. Some examples of pharmaceutical molecules containing *N*-(pyridin-2-yl)amides and imidazo[1,2-*a*]pyridines are shown in Fig. 1. Owing to the attractive biological properties of *N*-(pyridin-2-yl)amides and imidazo[1,2-*a*]pyridines, developing convenient synthetic methods, especially by which we can synthesize these two kinds of structures respectively from the same starting materials, is very meaningful.

Amides are ubiquitous in organic compounds, polymers, natural products, and pharmaceuticals.[4] Synthesis of amides is one of the most executed reactions in organic chemistry.[5] Pre-activated acyl halides or anhydrides are used as starting materials in traditional methods for constructing amide bond. Recently, many alternative substrates, such as aldehydes, alcohols, azides, aldoximes, nitriles and halides compounds had been employed for amide synthesis.[6] C–C bond cleavage is another developing approach to synthesize amides, but the excellent stability of C–C bond makes this subject develop slowly, exploring new methods for constructing amides directly by C–C bond cleavage is attractive. *N*-(Pyridin-2-yl)amide was previously synthesized *via* a Cu-catalyzed dehydrogenative reaction between aldehyde and aminopyridine in the presence of I_2 (Scheme 1a).[7] Adimurthy's group synthesized *N*-(pyridin-2-yl)amides *via* oxidative amidation of methylarenes using TBHP in decane.[8] Recently, two elegant works on Cu-catalyzed aerobic oxidative C–C bond cleavage for the preparation of *N*-(pyridin-2-yl)amide had been developed. Hwang *et al.* reported a visible-light-promoted aerobic oxidative C–N coupling between 2-aminopyridine and terminal alkynes through C≡C triple bond cleavage (Scheme 1b).[9] Kaliappan disclosed a biomimetic oxidation of methyl ketones for preparation of *N*-heterocyclic amides (Scheme 1c).[10] However, these methodologies suffer from several drawbacks, such as harsh reaction conditions, long reaction time and the use of transition metal complexes. Recently, we reported a metal-free method for synthesizing *N*-(pyridine-2-yl)amides from ketones *via* oxidative cleavage of C–C

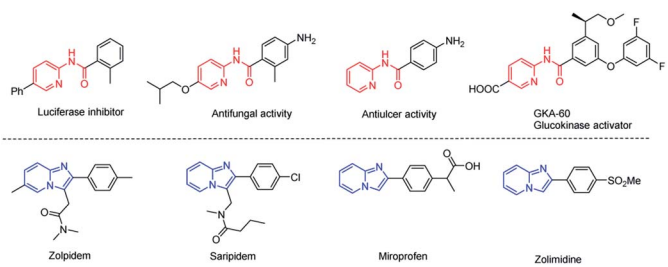

Fig. 1 Some pharmaceutical molecules based on pyridyl-amide and imidazopyridine.

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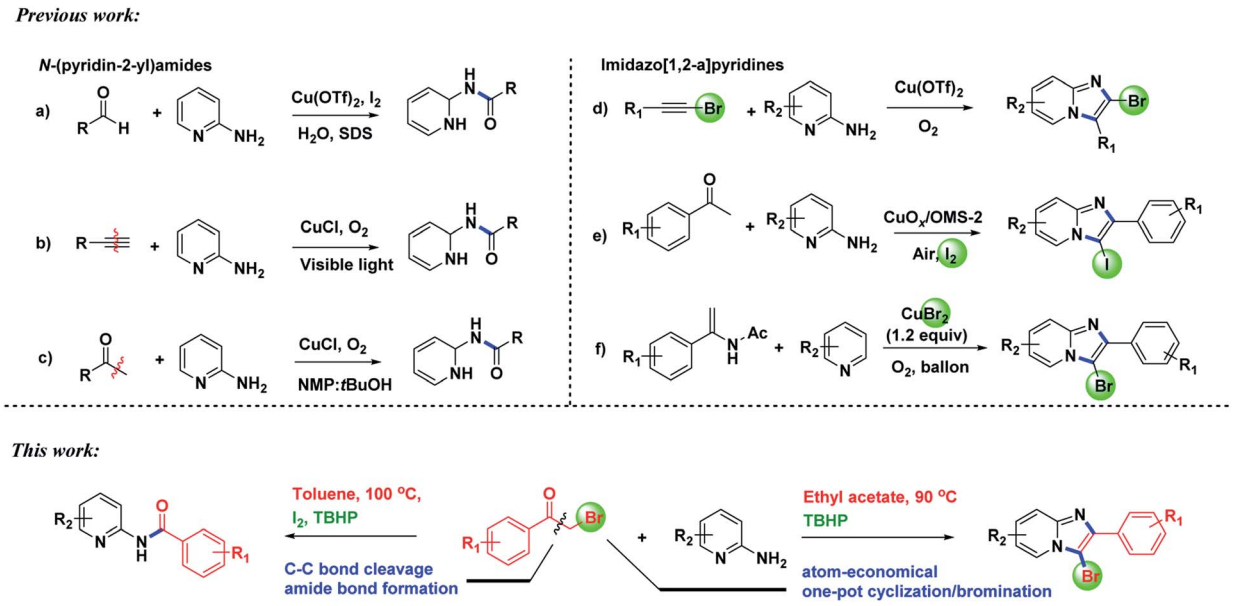

Scheme 1 Recent methods for the construction of pyridyl-amides and halosubstituted imidazopyridines.

bond in water.[11] Herein, we will continue to report the selective synthesis of *N*-(pyridine-2-yl)amides from α-bromoketones and 2-aminopyridine *via* controlling reaction conditions.

Intensive researches have been conducted to develop new and efficient strategies for constructing imidazo[1,2-*a*]pyridines.[12] Halo-substituted imidazo[1,2-*a*]pyridines are important building blocks and versatile synthons for preparing more complex imidazopyridines.[13] Classically, halo-substituted imidazo[1,2-*a*]pyri-dines are synthesized by the halogenation of imidazo[1,2-*a*]pyridines, such as Adimurthy's report.[14] for the synthesis of the intermediate imidazo[1,2-*a*]pyridines, base is generally needed.[15] While methods for direct synthesis of halo-substituted imidazo[1,2-*a*]pyridines in one-pot reaction without base were rarely reported. Jiang and co-workers reported a copper-catalyzed method for the synthesis of 2-halo-substituted imidazopyridines from haloalkynes and amino-pyridines (Scheme 1d).[16] 3-Iodoimidazopyridines were synthesized by Zhao and co-workers in the presence of copper supported on manganese oxide-based octahedral molecular sieves OMS-2 (CuOx/OMS-2) *via* tandem cyclization/iodination (Scheme 1e).[17] Yan and Huang's group reported copper bromide-mediated aerobic oxidative synthesis of 3-bromoimidazo[1,2-*a*]pyridines with pyridines and enamides (Scheme 1f).[18] Besides, metal-free tandem chlorocyclization of 2-amino-pyridines with carboxylic acids to synthesize chloro-substituted imidazopyridines was also described by Zeng's group.[19] However, these transformations over-relied on metal catalysts or stoichiometric excess of halogen sources. From the viewpoint of green chemistry, developing an atom-economical and metal-free approach to construct halo-substituted imidazo[1,2-*a*]pyridine is highly desirable.

Given the importance of *N*-(pyridin-2-yl)amides and imidazo[1,2-*a*]pyridines, chemodivergent synthesis of these two skeletons from same starting materials is very appealing. Herein, we developed a method to synthesize *N*-(pyridin-2-yl)amides and imidazo[1,2-*a*]pyridines respectively from α-bromoketones and 2-aminopyridine by controlling reaction conditions (Scheme 1).

Results and discussion

Traditionally, C–C bonds cleavage has been accomplished in the presence of transition-metal catalyst.[20] Initially, various metal catalysts were screened for the preparation of amide **3aa** from α-bromoacetophenone **1a** and 2-aminopyridine **2a** using 70% aqueous *tert*-butyl hydroperoxide (TBHP) as oxidant in toluene, but the yield of **3aa** was not pleasurable and the highest yield was only 17% in the presence of CuI (Table 1, entry 1). Surprisingly, after extensive screening, the desired amide **3aa** was obtained solely with yields of 83% and 79% respectively when I_2 or KI were used as the catalyst (Table 1, entries 4, 5). This transformation was sensitive to the types of the solvents and oxidants (Table 1, entries 6–8). Finally, the optimized reaction conditions for the synthesis of amides were obtained as follows: TBHP (4 equivalents) and iodine (20 mol%) in toluene at 100 °C for 2 hours (protocol A, Table 1, entry 9). Surprisingly, the 3-bromoimidazopyridine **4aa** was isolated with good yield when just using TBHP as oxidant in toluene (Table 1, entry 12). To further improve the yield of **4aa**, several solvents were screened, and the results showed that ethyl acetate was the most effective solvent for the preparation of **4aa** (Table 1, entry 14). Other oxidants such as H_2O_2 and oxygen (balloon) were also evaluated, however, the results were not pleasurable (entries 15–16). After extensive screening, **4aa** was successfully obtained in yield of 93% using 2 equivalents of TBHP as oxidant in ethyl acetate at 90 °C for 3 hours (protocol B, Table 1, entry 17).

With the optimized reaction conditions in hand, first, the scope of the oxidative amidation approach was examined with a range of α-bromoketones and aminopyridines. As shown in

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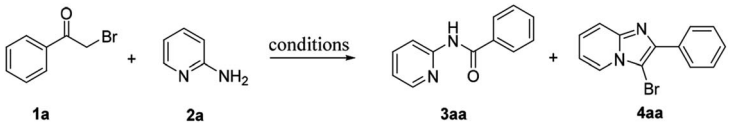
Table 1 Optimization of the reaction conditions[a]



Entry	Solvent	Oxidant[b] (4 eq.)	Catalyst (20 mol%)	Temp (°C)	t (h)	Yield[c] (%) 3aa	4aa
1	Toluene	TBHP	CuI	120	36	17	11
2	Toluene	TBHP	CuBr	120	36	3	73
3	Toluene	TBHP	$ZnBr_2$	120	36	—	5%
4	Toluene	TBHP	I_2	120	2	83	Trace
5	Toluene	TBHP	KI	120	2	79	Trace
6	DMF	TBHP	I_2	120	2	Trace	41
7	H_2O	TBHP	I_2	100	12	49	3
8	Toluene	H_2O_2	I_2	120	2	—	28
9	**Toluene**	**TBHP**	**I_2**	**100**	**2**	**84**	**Trace**
10	Toluene	—	—	120	2	—	—
11	Toluene	—	I_2	120	2	—	—
12	Toluene	TBHP	—	120	3	2	83
13	H_2O	TBHP	—	100	8	11	—
14	Ethyl acetate	TBHP	—	80	3	Trace	83
15	Ethyl acetate	H_2O_2	—	80	5	—	36
16	Ethyl acetate	O_2 (ballon)	—	80	3	—	—
17	**Ethyl acetate**	**TBHP (2 eq.)**	**—**	**90**	**3**	**Trace**	**93**

[a] Reaction conditions: **1a** (0.3 mmol), **2a** (0.45 mmol), oxidant (1.2 mmol), catalyst (0.06 mmol), solvent (2 mL). [b] 70% TBHP in water and 30% H_2O_2 in water were used. [c] Isolated yields.

Scheme 2, both the electron-rich (–Me, –OMe) and electron-withdrawing (–CF_3) groups on α-haloketones were well tolerated and produced the corresponding amides in good yields. Halo-substituted α-bromoketones can also afford desired amides in moderate to good yields (**3ca**, **3da**, **3ka**, **3la**). The steric factor has a slight effect on this transformation, as the meta-substituted α-bromoketones gave their corresponding products in moderate yields (**3ga**, **3ha**). Besides, heterocycle- and alkyl-substituted α-haloketones were also tested and gave corresponding amides in 70–87% yields (**3ma**, **3na**). Subsequently, the substrate scope of various 2-aminopyridines was investigated and the results showed that most of the substituted 2-aminopyridines could be transferred to their corresponding products in moderate to good yields.

Then, we evaluated various α-bromoketones 1 to examine the generality and limitations of the reaction for the synthesis of 3-bromoimidazopyridines, and the results was summarized in Scheme 3. Substrates with electron-withdrawing groups (–CF_3), electron-donating groups (–Me, –OMe) or halogen groups (–F, –Cl, –Br) on the para position of aromatic ring could be transferred to the corresponding products in good to excellent yields (**4ba–4ga**). Furthermore, substituents at the *meta* or *ortho* positions could also provide the corresponding products with good yields (**4ha–4ma**). Disubstituted or trisubstituted α-bromoacetophenones were all tolerated well (**4ha**, **4oa**). The product **4pa** bearing heteroaryl moiety was also obtained in 97% yield. Some alkyl-substituted α-bromoketones, like bromoacetone and ethyl bromopyruvate, could afford the desired products in good (**4qa**) or moderate (**4ra**) yield respectively. Next, we investigated the suitability of 2-aminopyridines and their heteroaromatic analogues. The results showed that 2-aminopyridines with substituents at the C-3, C-4, C-5 position reacted smoothly to give their products in moderate yields (**4ab–4ad**, **4af**, **4ag**). This reaction is highly sensitive to the presence of a substituent at the C-6 position of pyridine ring attributed to steric hindrance (**4ae**).[21] Besides, other *ortho*-amino-nitrogen-containing heteroaromatic derivatives were also investigated, and the results demonstrated that isoquinolin-1-amine was tolerated in this cascade transformation and could be transferred to products with good to excellent yields, while pyrimidin-2-amine (**4ai**) and 2-aminothiazole (**4aj**) were not suit well for this reaction.

3-Iodoimidazo[1,2-*a*]pyridine could also be prepared using this methology in moderate yield (Scheme 4a). Moreover, the synthetic utility of 3-bromoimidazo[1,2-*a*]pyridines were explored, C3-arylation and alkynylation reactions processed smoothly through a classical Pd-catalyzed cross-coupling strategy (Schemes 4b and c). Overall, this simple, metal-free protocol could be extended as an efficient and practical method to construct more complex C-3-substituted imidazopyridines.

To understand the mechanism of this tandem reaction, control experiments were carried out (Scheme 5). **5aa** was isolated in both reactions (Scheme 5, **1**). In protocol A, the reaction was suppressed remarkably when 2 equivalents of TEMPO, a radical

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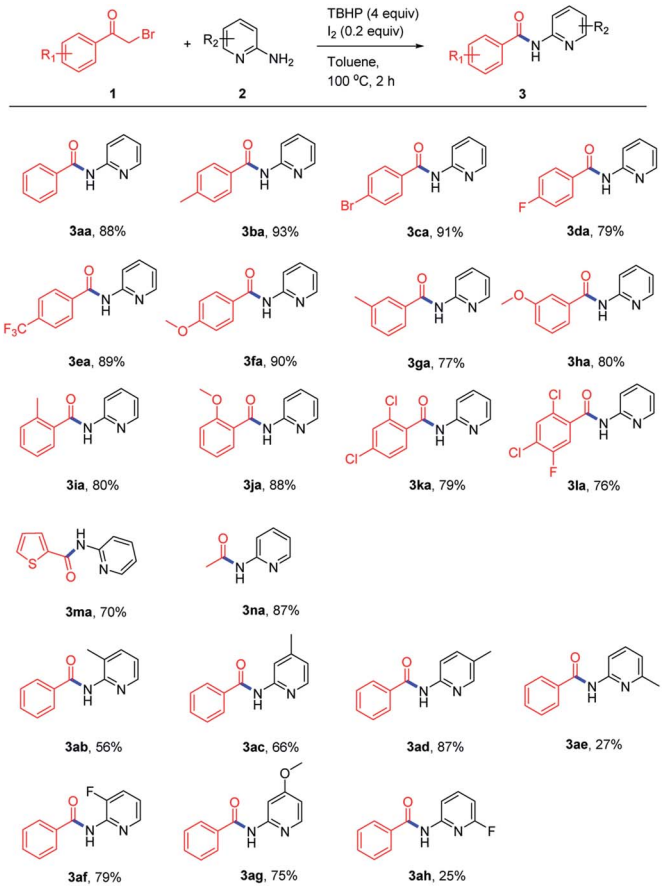
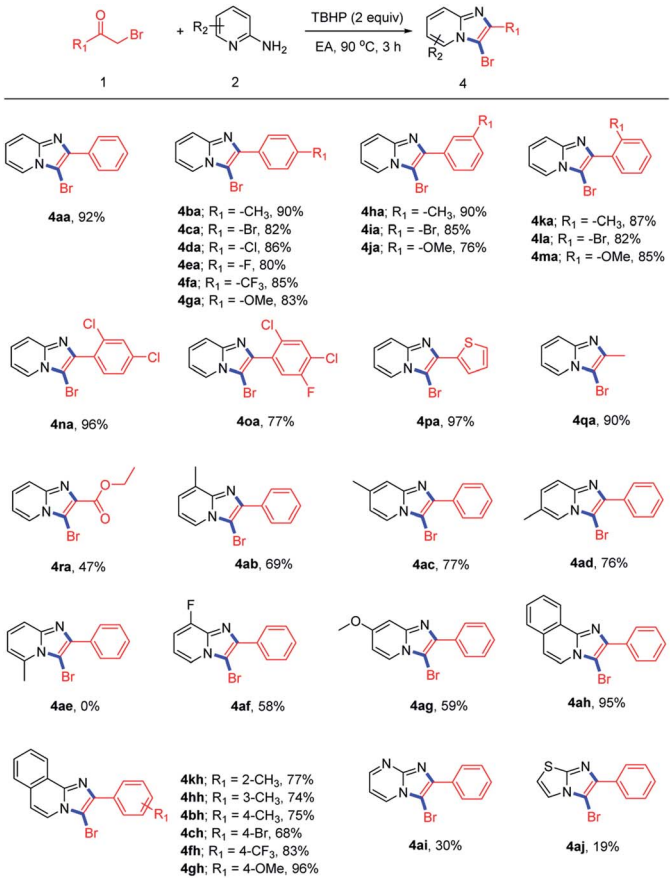


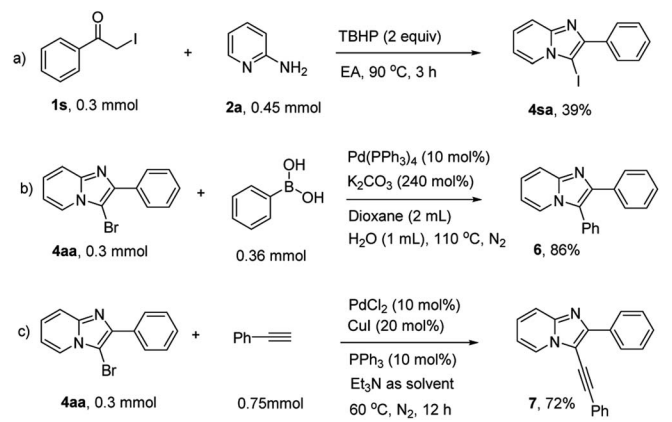
Scheme 2 Constructing amides 3 directly from α-haloketones **1** and 2-aminopyridines **2**. [a]Reaction conditions: **1** (0.3 mmol), **2** (0.45 mmol), TBHP (1.2 mmol), I_2 (0.06 mmol), toluene (2 mL), 100 °C, 2 h.



Scheme 3 Constructing 3-bromoimidazo[1,2-*a*]pyridines directly from α-haloketones **1** and 2-aminopyridines **2**. [a]Reaction conditions: **1** (0.3 mmol), **2** (0.45 mmol), TBHP (0.6 mmol), EA (2 mL), 90 °C, 3 h.

trapping reagent, was added into the reaction system, indicating that the reaction might proceed *via* a free radical process (Scheme 5, **1**). We speculated that **5aa** was the key intermediate for these two reactions. Thus, some control experiments based on **5aa** were conducted. **4aa** was obtained in 42% yield when **5aa** was subjected to HBr (1 equivalent) and TBHP (2 equivalents) (Scheme 5, **4**) and **5aa** reacted with Br_2 could also form **4aa** in 88% yield (Scheme 5, **5**), these results showed that the bromine was formed during the synthesis of 3-bromoimidazo[1,2-*a*]pyridines. Furthermore, when 1-cyclohexen-1-ylbenzene was added to consume the *in situ* generated bromine, no desired 3-bromo-2-phenylimidazo[1,2-*a*]pyridine was observed (Scheme 5, **6**). On the other hand, the amide product **3aa** could be obtained from **5aa** in I_2/TBHP system (Scheme 5, **2**) or only TBHP for longer time (Scheme 5, **3**). Besides, no amide product (**3aa**) was obtained from 3-bromo-imidazopyridine (**4aa**) or 3-iodoimidazopyridine (**4sa**), which illustrated that **4aa** could not be further transferred to **3aa**. These results collectively indicated that there was a fierce competition between amidation and bromination, the iodine played an extremely important role in this C–C bond cleavage reaction.

Based on the above results and previous knowledge, we proposed a plausible mechanism for this chemodivergent reaction.[22] As shown in Scheme 6, the reaction proceeded *via* the initial displacement of the halogen atom by the pyridine ring nitrogen to afford pyridinium salt (**8**), which subjected a facile closure and provided the shared intermediate **5aa**. In protocol A, *t*-BuO•, which was generated in I_2/TBHP system,[23] attacked the double bond of **5aa** to afford 9, 9 subsequently transferred to **11**. Then, oxygen radical **12** was formed under *t*-



Scheme 4 Investigation of the versatility of this strategy.

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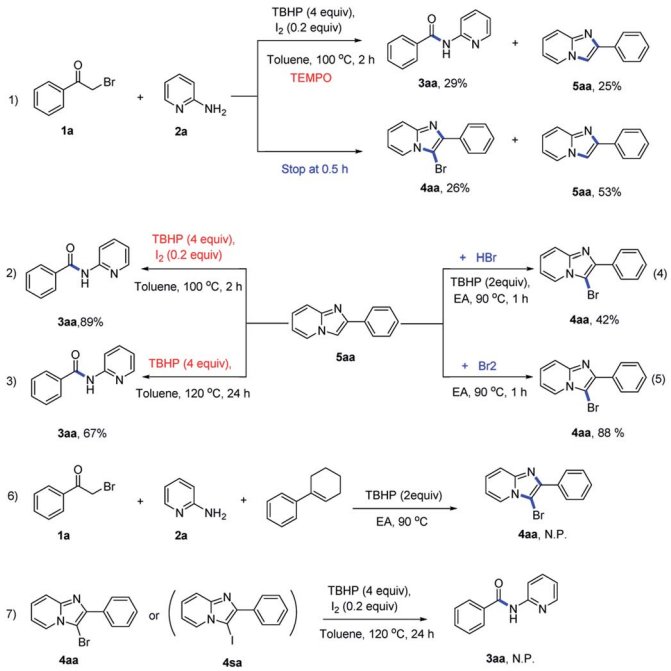
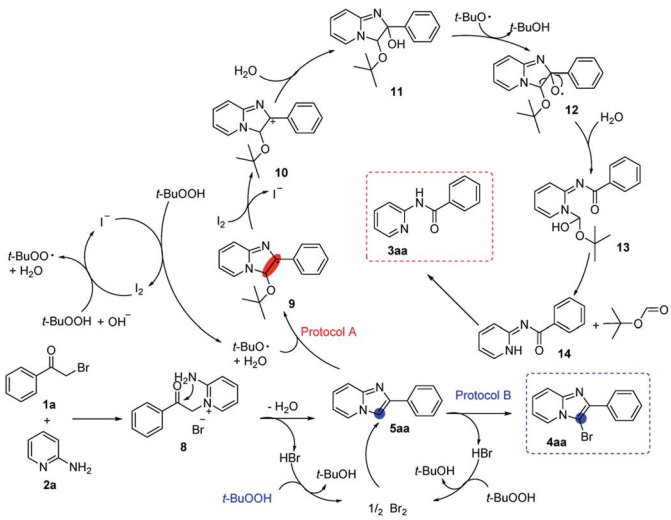


Scheme 5 Control experiments.



Scheme 6 Proposed reaction mechanism.

BuO•, **12** further transformed to **13** by C–C bond cleavage.[10,20a,22e,24] Next, a *tert*-butyl formate was released from **13** leading to the formation of amide **14**,[25] which proceed an isomerization to afford the desired amide **3aa**. In protocol B, the released hydrogen bromide was converted into bromine by oxidation of TBHP. The bromination of **5aa** yielded the target molecule **4aa** and the released hydrogen bromide could be oxidized to bromine and used for bromination again.

Conclusions

In conclusion, we have developed a divergent synthesis of pyridyl-amides and imidazopyridines from simple α-bromoketones and 2-aminopyridine. Various *N*-(pyridin-2-yl) amides or 3-bromo-imidazopyridines were obtained in moderate to good yields with high selectivity by tuning the catalyst. The one-pot tandem cyclization/bromination of α-bromoketones with 2-aminopyridine in the presence of TBHP provided versatile 3-bromo-imidazopyridines with excellent functional group tolerance and scalability. The α-haloketone acted as both the substrate and the bromo source, and the avoidance of transition-metal, fewer synthetic steps and high atom-economy make this protocol attractive. Whereas, the addition of I_2 promote the oxidative C–C bond cleavage amidation afforded *N*-(pyridin-2-yl)amides in a metal-free condition. Less activity demonstrated by other metal catalysts suggested that I_2 played a vital role in this reaction. C–C bond cleavage amidation is still a difficult and significant subject especially in modification and semisynthesis of natural medicine, which can simplify the synthetic procedure and make the semisynthesis more available. Iodine as a catalyst in C–C bond cleavage amidation is rarely reported. We believe our work will be useful for completing the C–C bond cleavage amidation field.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Notes and references

1 (*a*) C. Annoni, T. Endoh, D. Hnedzko, E. Rozners and N. Sugimoto, *Chem. Commun.*, 2016, **52**, 7935; (*b*) T. L. Harris, C. J. Wenthur, A. Diego-Taboada, G. Mackenzie, T. S. Corbitt and K. D. Janda, *Chem. Commun.*, 2016, **52**, 4187; (*c*) P. Sakthivel, A. Ilangovan and M. P. Kaushik, *Eur. J. Med. Chem.*, 2016, **122**, 302; (*d*) H. Y. Wang, Y. Qin, H. Li, L. J. Roman, P. Martásek, T. L. Poulos and R. B. Silverman, *J. Med. Chem.*, 2016, **59**, 4913; (*e*) E. R. Baral, K. Sharma, M. S. Akhtar and Y. R. Lee, *Org. Biomol. Chem.*, 2016, **14**, 10285.

2 (*a*) L. Ferrins, M. Gazdik, R. Rahmani, S. Varghese, M. L. Sykes, A. J. Jones, V. M. Avery, K. L. White, E. Ryan, S. A. Charman, M. Kaiser, C. A. S. Bergstrom and J. B. Baell, *J. Med. Chem.*, 2014, **57**, 6393; (*b*) L. H. Heitman, J. P. D. van Veldhoven, A. M. Zweemer, K. Ye, J. Brussee and A. P. IJzerman, *J. Med. Chem.*, 2008, **51**, 4724; (*c*) S. S. Kulkarni, B. Nightingale, C. M. Dersch, R. B. Rothmanb and A. H. Newman, *Bioorg. Med. Chem. Lett.*, 2006, **16**, 3371; (*d*) K. Xu, Z. Y. Xiao, Y. B. Tang, L. Huang, C. H. Chen, E. Ohkoshi and K. H. Lee, *Bioorg. Med. Chem. Lett.*, 2012, **22**, 2772.

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3 (*a*) G. Richa, L. Vijay and P. Kamaldeep, *Curr. Top. Med. Chem.*, 2016, **16**, 3590; (*b*) T. L. Kishbaugh, *Curr. Top. Med. Chem.*, 2016, **16**, 3274; (*c*) C. Ravi and S. Adimurthy, *Chem. Rec.*, 2017, **17**, 1; (*d*) J. B. Xi, Y. F. Fang, B. Frett, M. L. Zhu, T. Zhu, Y. N. Kong, F. J. Guan, Y. Zhao, X. W. Zhang, H. Y. Li, M. L. Ma and W. H. Hu, *Eur. J. Med. Chem.*, 2017, **126**, 1083; (*e*) J. Dam, Z. Ismail, T. Kurebwa, N. Gangat, L. Harmse, H. M. Marques, A. Lemmerer, M. L. Bode and C. B. de Koning, *Eur. J. Med. Chem.*, 2017, **126**, 353.

4 (*a*) R. Takise, K. Muto and J. Yamaguchi, *Chem. Soc. Rev.*, 2017, **46**, 5864; (*b*) Y. K. Zhang, J. J. Plattner, E. E. Easom, R. T. Jacobs, D. Guo, Y. R. Freund, P. Berry, V. Ciaravino, J. C. L. Erve, P. J. Rosenthal, B. Campo, F. J. Gamo, L. M. Sanz and J. Cao, *J. Med. Chem.*, 2017, **60**, 5889; (*c*) B. M. Trost, J. J. Cregg and N. Quach, *J. Am. Chem. Soc.*, 2017, **139**, 5133.

5 (*a*) V. R. Pattabiraman and J. W. Bode, *Nature*, 2011, **480**, 471; (*b*) P. K. Mykhailiuk, V. Kubyshkin, T. Bach and N. Dudisa, *J. Org. Chem.*, 2017, **82**, 8831; (*c*) S. Fuse, Y. Mifune, H. Nakamura and H. Tanaka, *Nat. Commun.*, 2016, **7**, 13491; (*d*) H. M. Burke, L. McSweeney and E. M. Scanlan, *Nat. Commun.*, 2017, **8**, 15655.

6 (*a*) R. M. de Figueiredo, J. S. Suppo and J. M. Campagne, *Chem. Rev.*, 2016, **116**, 12029; (*b*) H. Lundberg, F. Tinnis, N. Selander and H. Adolfsson, *Chem. Soc. Rev.*, 2014, **43**, 2714; (*c*) A. Ojeda-Porras and D. Gamba-Sánchez, *J. Org. Chem.*, 2016, **81**, 11548; (*d*) G. N. Papadopoulos and C. G. Kokotos, *J. Org. Chem.*, 2016, **81**, 7023; (*e*) T. B. Halima, J. K. Vandavasi, M. Shkoor and S. G. Newman, *ACS Catal.*, 2017, **7**, 2176; (*f*) R. M. de Figueirede, J. S. Suppo, C. Midrier and J. M. Campagne, *Adv. Synth. Catal.*, 2017, **359**, 1963; (*g*) C. W. Cheung, M. L. Ploeger and X. Hu, *Nat. Commun.*, 2017, **8**, 14878.

7 O. P. S. Patel, D. Anand, R. K. Maurya and P. O. Yadav, *Green Chem.*, 2015, **17**, 3728.

8 V. Pappula, C. Ravi, S. Samanta and S. Adimurthy, *ChemistrySelect*, 2017, **2**, 5887.

9 A. Ragupathi, A. Sagadevan, C. C. Lin, J. R. Hwu and K. C. Hwang, *Chem. Commun.*, 2016, **52**, 11756.

10 P. Subramanian, S. Indu and K. P. Kaliappan, *Org. Lett.*, 2014, **16**, 6212.

11 Y. P. Liu, H. H. Sun, Z. J. Huang, C. Ma, A. J. Lin, H. Q. Yao, J. Y. Xu and S. T. Xu, *J. Org. Chem.*, 2018, **83**, 14307.

12 (*a*) Q. D. Wen, P. Lu and Y. G. Wang, *Chem. Commun.*, 2015, **51**, 15378; (*b*) H. Y. Zhan, L. M. Zhao, J. Q. Liao, N. Y. Li, Q. L. Chen, S. X. Qiu and H. Cao, *Adv. Synth. Catal.*, 2015, **357**, 46; (*c*) D. C. Mohan, R. R. Donthiri, S. N. Rao and S. Adimurthy, *Adv. Synth. Catal.*, 2013, **355**, 2217; (*d*) A. K. Bagdi, M. Rahman, S. Santra, A. Majee and A. Hajra, *Adv. Synth. Catal.*, 2013, **355**, 1741; (*e*) Z. J. Cai, S. Y. Wang and S. J. Ji, *Adv. Synth. Catal.*, 2013, **355**, 2686; (*f*) C. He, J. Hao, H. Xu, Y. P. Mo, H. Y. Liu, J. J. Han and A. W. Lei, *Chem. Commun.*, 2012, **48**, 11073.

13 (*a*) S. Kumar, N. Sharma, I. K. Maurya, A. K. K. Bhasin, N. Wangoo, P. Brandão, V. Félix, K. K. Bhasin and R. K. Sharma, *Eur. J. Med. Chem.*, 2016, **123**, 916; (*b*) D. Dheer, K. R. Reddy, S. K. Rath, P. L. Sangwan, P. Das and R. Shankar, *RSC Adv.*, 2016, **6**, 38033; (*c*) F. Lovering, C. Aevazelis, J. Chang, C. Dehnhardt, L. Fitz, S. Han, K. Janz, J. Lee, N. Kaila, J. McDonald, W. Moore, A. Moretto, N. Papaioannou, D. Richard, M. S. Ryan, Z. K. Wan and A. Thorarense, *ChemMedChem*, 2016, **11**, 217.

14 R. Semwal, C. Ravi, R. Kumar, R. Meena and S. Adimurthy, *J. Org. Chem.*, 2019, **84**, 792.

15 (*a*) H. M. Su, L. Y. Wang, H. H. Rao and H. Xu, *Org. Lett.*, 2017, **19**, 2226; (*b*) H. Kim, M. Byeon, E. Jeong, Y. Baek, S. J. Jeong, K. Um, S. H. Han, G. U. Han, G. H. Ko, C. Maeng, J. Y. Son, D. Kim, S. H. Kim, K. Lee and P. H. Lee, *Adv. Synth. Catal.*, 2019, **361**, 2094.

16 Y. Gao, M. Z. Yin, W. Q. Wu, H. W. Huang and H. F. Jiang, *Adv. Synth. Catal.*, 2013, **355**, 2263.

17 X. Meng, C. Y. Yu, G. X. Chen and P. Q. Zhao, *Catal. Sci. Technol.*, 2015, **5**, 372.

18 X. Q. Zhou, H. Yan, C. W. Ma, Y. Q. He, Y. M. Li, J. H. Cao, R. L. Yan and G. S. Huang, *J. Org. Chem.*, 2016, **81**, 25.

19 X. S. Xiao, Y. Xie, S. Y. Bai, Y. F. Deng, H. F. Jiang and W. Zeng, *Org. Lett.*, 2015, **17**, 3998.

20 (*a*) X. Q. Huang, X. Y. Li, M. C. Zou, S. Song, C. H. Tang, Y. Z. Yuan and N. Jiao, *J. Am. Chem. Soc.*, 2014, **136**, 14858; (*b*) D. W. Flaherty, D. D. Hibbitts and E. Iglesia, *J. Am. Chem. Soc.*, 2014, **136**, 9664.

21 (*a*) M. Matsumura, Y. Sakata, A. Iwase, M. Kawahata, Y. Kitamura, Y. Murata, N. Kakusawa, K. Yamaguchi and S. Yasuike, *Tetrahedron Lett.*, 2016, **57**, 5484; (*b*) Z. Fei, Y. P. Zhu, M. C. Liu, F. C. Jian and A. X. Wu, *Tetrahedron Lett.*, 2013, **54**, 1222.

22 (*a*) A. J. Elliott, H. Guzik and J. R. Soler, *J. Heterocycl. Chem.*, 1982, **19**, 1437; (*b*) M. Jafarzadeh, E. Soleimani, H. Sepahvand and R. Adnan, *RSC Adv.*, 2015, **5**, 42744; (*c*) L. J. Ma, X. P. Wang, W. Yu and B. Han, *Chem. Commun.*, 2011, **47**, 11333; (*d*) C. D. Huo, J. Tang, H. S. Xie, Y. J. Wang and J. Dong, *Org. Lett.*, 2016, **18**, 1016; (*e*) K. Yan, D. S. Yang, W. Wei, G. Q. Li, M. Y. Sun, Q. Y. Zhang, L. J. Tian and H. Wang, *RSC Adv.*, 2015, **5**, 100102; (*f*) W. K. Luo, X. Shi, W. Zhou and L. Yang, *Org. Lett.*, 2016, **18**, 2036; (*g*) Z. J. Liu, J. Zhang, S. L. Chen, E. Shi, Y. Xu and X. B. Wan, *Angew. Chem., Int. Ed. Engl.*, 2012, **51**, 323.

23 G. Schmitz, *Phys. Chem. Chem. Phys.*, 2001, **3**, 4741.

24 C. H. Tang and N. Jiao, *Angew. Chem., Int. Ed.*, 2014, **53**, 6528.

25 (*a*) F. Effenberger, M. Keill and u. E. Bessey, *Chem. Ber.*, 1980, **113**, 2110; (*b*) M. Suchy, A. A. H. Elmehriki and R. H. E. Hudson, *Org. Lett.*, 2011, **13**, 3952.

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