

Cite this: *Chem. Sci.*, 2021, 12, 4034

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 2nd December 2020
Accepted 17th January 2021

DOI: 10.1039/d0sc06603f

rsc.li/chemical-science

Metal-free C(sp³)-H functionalization of sulfonamides via strain-release rearrangement†

Jiefeng Hu,^a Xianyu Yang,^a Shasha Shi,^a Bo Cheng,^a Xiaoling Luo,^{*c} Yu Lan^{*d} and Teck-Peng Loh^{*ab}

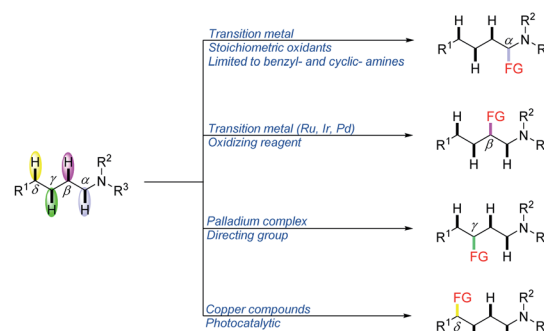
With the increasing awareness of sustainable chemistry principles, the development of an efficient and mild strategy for C(sp³)-H bond activation of nitrogen-containing compounds without the utilization of any oxidant and metal is still highly desired and challenging. Herein, we present a metal-free reaction system that enables C-H bond functionalization of aliphatic sulfonamides using DABCO as a promoter under mild conditions, affording a series of α,β -unsaturated imines in good yields with high selectivities. This protocol tolerates a broad range of functionalities and can serve as a powerful synthetic tool for the late-stage modification of complex compounds. More importantly, control experiments and detailed DFT calculations suggest that this process involves [2 + 2] cyclization/ring-cleavage reorganization, which opens up a new platform for the establishment of other related reorganization reactions.

Introduction

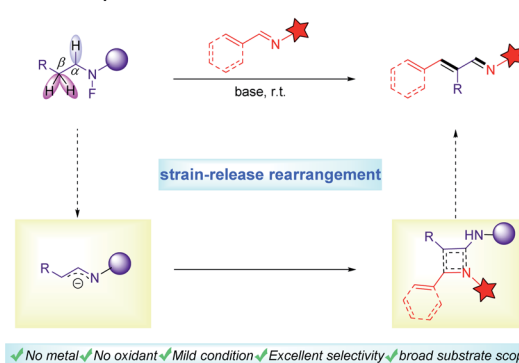
Nitrogen-containing compounds are present widely in a broad range of natural, pharmaceutical and synthetic compounds. In the past ten years, considerable effort has been directed toward the exploration of their organic synthesis methodologies. Among the various methods reported, direct activation of unreactive C-H bonds in amine derivatives for coupling reactions is one of the most effective and important strategies. In this context, early research has focused primarily on α -C-H bond functionalization of amines using transition metal catalysts with stoichiometric amounts of oxidants.¹ In recent years, activation of more remote C-H bonds in compounds containing nitrogen has attracted great attention and interest. For example, γ -C-H activation of amines was achieved by Yu's group using a palladium complex as the catalyst in combination with a directing group.² On the other hand, δ -C-H bond functionalization in sulfonamides has been accomplished through 1,5-hydrogen atom transfer of amidyl radicals in the presence of a copper catalyst.³ Given the medicinal value of β -substituted

amine derivatives,⁴ some methods for β -C-H functionalization have been developed based on an oxidative cross-coupling pathway (Scheme 1A).^{5,6} These reactions often require transition metals (Ru, Ir, Pd and Fe),^{7–10} oxidizing reagents¹¹ and high

A Selective activation of C-H bonds in amine derivatives.



B Metal-free multiple C-H functionalization of sulfonamides.



^aInstitute of Advanced Synthesis, School of Chemistry and Molecular Engineering, Jiangsu National Synergetic Innovation Center for Advanced Materials, Nanjing Tech University, Nanjing 211816, China. E-mail: iasjfh@njtech.edu.cn

^bDivision of Chemistry and Biological Chemistry, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore

^cChongqing Key Laboratory of Inorganic Functional Materials, College of Chemistry, Chongqing Normal University, Chongqing 401331, China

^dCollege of Chemistry, Institute of Green Catalysis, Zhengzhou University, Zhengzhou, Henan, 450001, China

† Electronic supplementary information (ESI) available. CCDC 2025337. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0sc06603f

Scheme 1 Development of a novel process. FG, functional group.

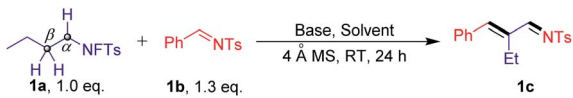
temperature.¹² In contrast, transition metal-free protocols are very rare in this field. In 2014, Seidel *et al.* reported a redox-neutral α,β -difunctionalization cascade reaction of cyclic amines under microwave irradiation at 200 °C.¹³ In 2018, Chang *et al.* presented a B(C₆F₅)₃-catalyzed β -C–H silylation of *N*-aryl piperidines with hydrosilanes at 120 °C.¹⁴ Notably, Seidel *et al.* used organolithium reagents to achieve multi-C–H functionalization of alicyclic amines. And a key intermediate, the *in situ*-generated endocyclic 1-azaallyl anion, was proposed in this report.¹⁵ Despite these advances in cyclic amines, the development of a mild and metal-free approach for the functionalization of C–H bonds in aliphatic amides is extremely challenging.

Imines are ubiquitous and valuable intermediates in the synthesis of nitrogen-containing compounds, pharmaceuticals and natural products.^{16–19} Among many different imines, α,β -unsaturated imines are a unique class of difunctionalized compounds and play key roles in the synthesis of heterocycles and pharmaceuticals.²⁰ Traditionally, these compounds are synthesized through aldol-type condensation of aldehydes, followed by dehydrative condensation with amines.²¹ Unfortunately, these condensation reactions usually suffer from harsh acidic conditions and high temperatures, and require dehydrating apparatus. On the other hand, some aldehydes, as reaction substrates, are not easily available and unstable, especially due to aerial oxidation. In addition, the conjugated imines obtained through this strategy are very difficult to purify because they are frequently mixed with other isomers. Thus, the widespread application of α,β -unsaturated imines is extremely hindered. Notably, in recent years significant progress has been made in the selective oxidation of amines for the synthesis of imines based on biocatalysts,^{22–25} complex metal catalysts^{26–32} or oxidizing reagents.^{33,34} However, their substrates are limited to benzylamines and cyclic amines.³⁵ Actually, the oxidation of amides is more difficult than that of amines because their nitrogen atoms have much lower electron density.³⁶ Moreover, it is very important³⁷ and challenging to directly synthesize unsaturated imines through dehydrogenation of amine derivatives. Hence, we report an efficient metal-free system for the synthesis of α,β -unsaturated imines with high geometrical selectivities through multiple C–H bond functionalization of *N*-fluoro sulfonamides under mild conditions (Scheme 1B). It is noteworthy that this pathway proceeded *via* a four-membered ring reorganization process.

Results and discussion

Initial studies involved the evaluation of the selective cross-coupling reaction of the *N*-fluorotosylamide derivative **1a** with *N*-tosylbenzaldimine **1b** (Table 1). The reaction was found to be feasible in the presence of K₂CO₃ (2.0 equiv.) in DMF at room temperature, providing the *N*-((*E*)-2-((*E*)-benzylidene)butylidene)-4-methylbenzenesulfonamide (**1c**) in an isolated yield of 29% (entry 1). Other inorganic bases, such as K₃PO₄ and CsOAc, also showed low yields (entries 2 and 3). Strong bases (KOH) inhibited the progress of the reaction (entry 4). To our delight, organic bases have high reactivity for this cross-coupling reaction (entries 5–7). When 1.0 equiv. DABCO was

Table 1 Reaction development^a



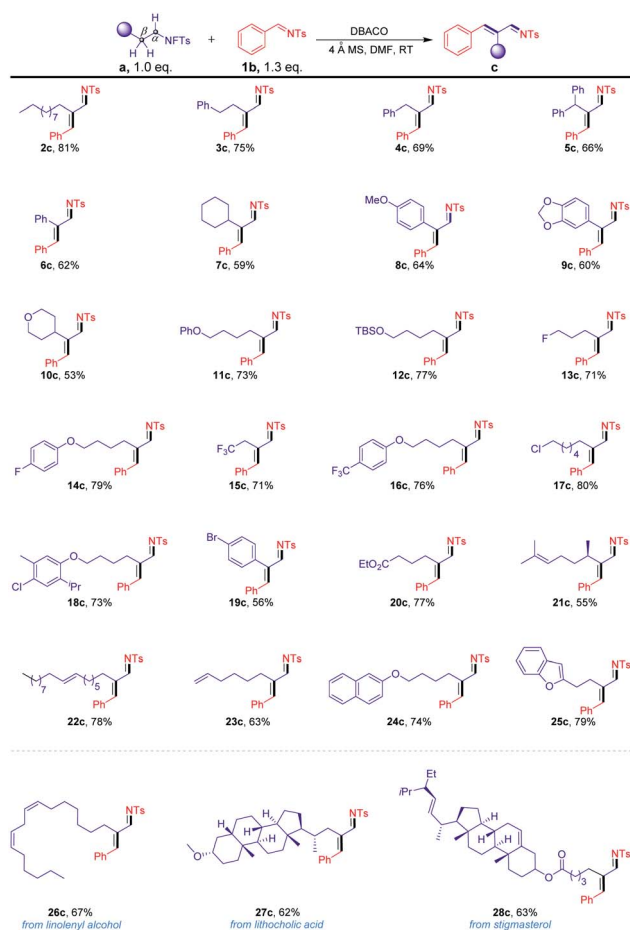
Entry	Base	Solvent	Yield ^b (%)
1	K ₂ CO ₃	DMF	29
2	CsOAc	DMF	26
3	K ₃ PO ₄	DMF	31
4	KOH	DMF	Trace
5	Et ₃ N	DMF	65
6	DBU	DMF	53
7	DABCO	DMF	81
8 ^c	DABCO	DMF	80
9	—	DMF	N
10 ^d	DABCO	DMF	72
11	DABCO	MeCN	58
12	DABCO	THF	39
13	DABCO	DCE	38
14	DABCO	Toluene	N

^a Reaction conditions: **1a** (0.20 mmol), **1b** (0.26 mmol), 1.0 equiv. base and 150 mg 4 Å molecular sieves in solvent (1.0 mL), 24 h, at room temperature, under Ar. ^b Isolated yield. ^c Using 30 mol% DABCO. ^d After removing molecular sieves. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene, DABCO = 1,4-diazabicyclo[2.2.2]octane, DMF = *N,N*-dimethylformamide, Ts = 4-toluenesulfonyl.

added as a base in this system, the yield of **1c** was dramatically increased to 81% and no other isomers were detected. It is important to note that the high yield of imine products could still be maintained even when the DABCO loading was decreased to 30 mol% (entry 8). As expected, removal of the base resulted in no reaction (entry 9). This result illustrates that DABCO is an essential driving force for this transformation. It is noteworthy that when 4 Å molecular sieves were removed, the product was obtained in a slightly lower yield of 72% (entry 10). Additionally, reactions carried out in other polar aprotic solvents, such as MeCN, THF and DCE, furnished the product in lower yields (entries 11–13). Finally, no products were observed using toluene as the solvent (entry 14).

With this exciting initial result in hand, we proceeded to investigate the scope of the reactions using various *N*-fluorotosylamides, prepared from the corresponding alkyl amines (Scheme 2). As shown, *N*-fluorotosylamide substrates with different carbon chains were efficiently transformed into the corresponding α,β -unsaturated imines in moderate to excellent yields (**2c–7c**). These results revealed that the products were obtained in lower yields with sterically bulky substrates. The products with substituted alkyl ethers, phenolic ethers and silyl ethers were formed in good yields (**8c–12c**). It should be noted that the reaction was not affected by halo substituents such as F, CF₃, Cl and Br on the substrates (**13c–19c**), highlighting its potential in combination with the subsequent cross-coupling transformations. Under our conditions, ester-containing substrate **20c** also worked well. In particular, the substrates **21c–23c**, which contained an alkenyl motif, were also found to be compatible with the reaction conditions. Excitingly,

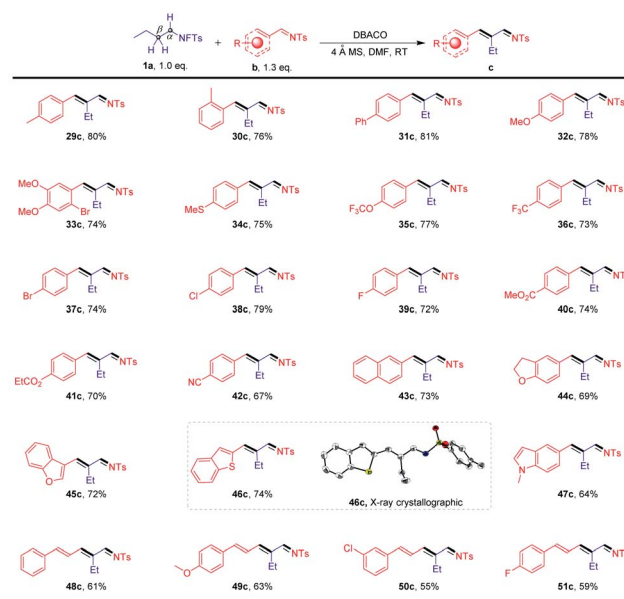




Scheme 2 Substrate scope of alkylamine derivatives. Reaction conditions: a mixture of *N*-fluorotosylamides **a** (0.20 mmol), *N*-tosylbenzalimine **b** (0.30 mmol), 150 mg 4 Å molecular sieves and DABCO (0.20 mmol) in DMF (1 mL) was stirred for 24 h at room temperature under Ar, isolated yield after chromatography. TBS = *tert*-butyldimethylsilyl.

naphthalene (**24c**) and benzofuran (**25c**) were also shown to exhibit high levels of reactivities. To showcase the utility of the transformation for diversifying natural product amines, we prepared a diverse collection of *N*-fluorotosylamide derivatives and subjected them to the optimized reaction conditions. For example, our strategy has been applied in the modification of *N*-fluorotosylamide **26a** with two *cis*-alkene groups from linolenyl alcohol, generating product **26c** in 67% yield. The steroid derivative **27a** was also readily transformed into the α,β -unsaturated imine **27c** in 62% yield. Moreover, the *N*-fluorotosylamide **28a**, which was synthesized from stigmasterol derivatives by a series of synthetic methods, could also be converted into the desired product **28c** in 63% yield.

The scope of this transformation was further evaluated using *N*-fluorotosylamide (**1a**) in conjunction with a more diverse pool of arylimines (**b**) as shown in Scheme 3. A wide range of substituted imines that possess electron-neutral, electron-donating, and electron-withdrawing substituents were readily tolerated (**29c–51c**). Among them, the substrate bearing a CN group afforded the desired product in 67% yield (**42c**).

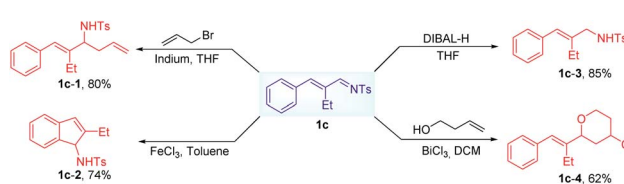


Scheme 3 Substrate scope of arylimines. Reaction conditions: a mixture of *N*-fluorotosylamide **1a** (0.20 mmol), *N*-tosylbenzalimines **b** (0.26 mmol), 150 mg 4 Å molecular sieves and DABCO (0.20 mmol) in DMF (1 mL) was stirred for 24 h at room temperature under Ar, isolated yield after chromatography.

Furthermore, the presence of oxygen-, sulfur- and nitrogen-containing heterocycles (**44c–47c**) did not interfere with the reactions. Notably, the structure of one of the products obtained, **46c**, was characterized by X-ray crystallographic analysis. We were also pleased to observe that this method can be applied to some more challenging substrates. For instance, a series of π -extended systems could also participate in the transformation to afford the conjugated imines **48c–51c** in moderate yields.

We next investigated the potential of α,β -unsaturated imines in the subsequent synthetic transformations. For example, allylamine compounds can be formed in the presence of DIBAL-H at -78°C . And we also explored the metal-mediated allylation of **1c** in THF, obtaining the corresponding product with a yield of 80%. Under the catalysis of FeCl_3 , the formed imines can undergo a cyclization reaction to provide indenamine derivatives. Interestingly, the synthetic utility of the formed unsaturated imine was further demonstrated through Prins cyclization reactions (Scheme 4).

Several experiments were conducted to provide insight into the potential mechanism of this cross-coupling reaction. (1) When using TEMPO and BHT as free radical inhibitors, this reaction was not completely suppressed. These results imply that

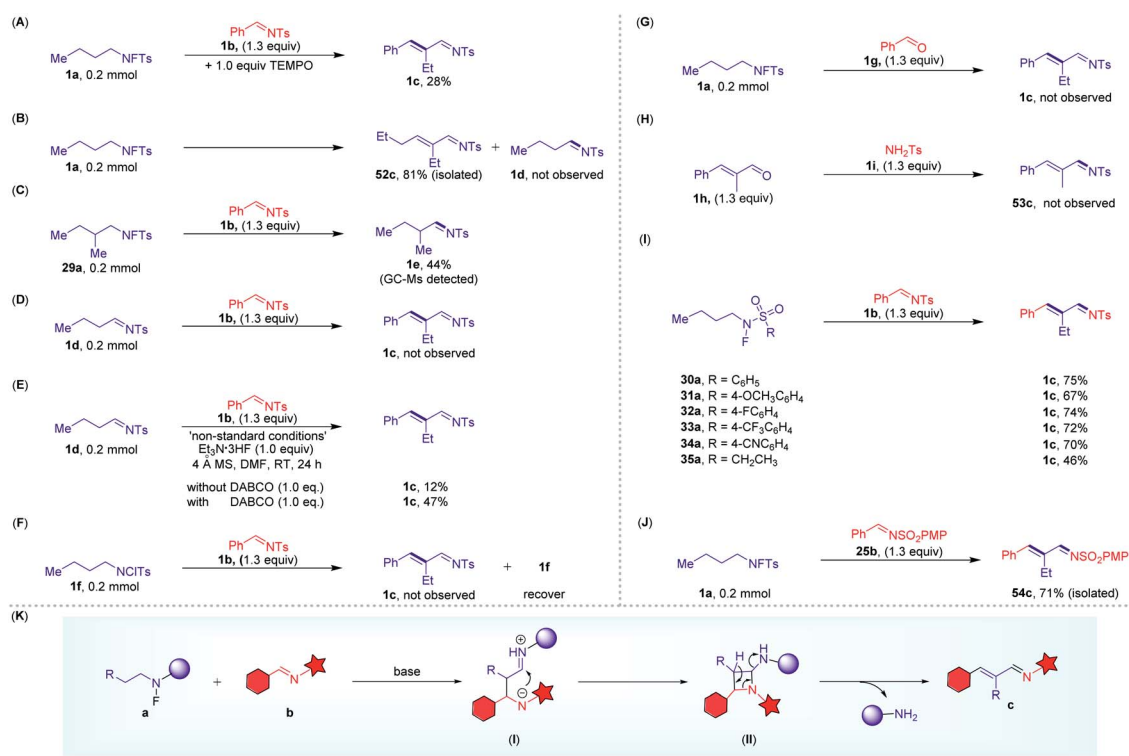


Scheme 4 Utility of the formed α,β -unsaturated imines.

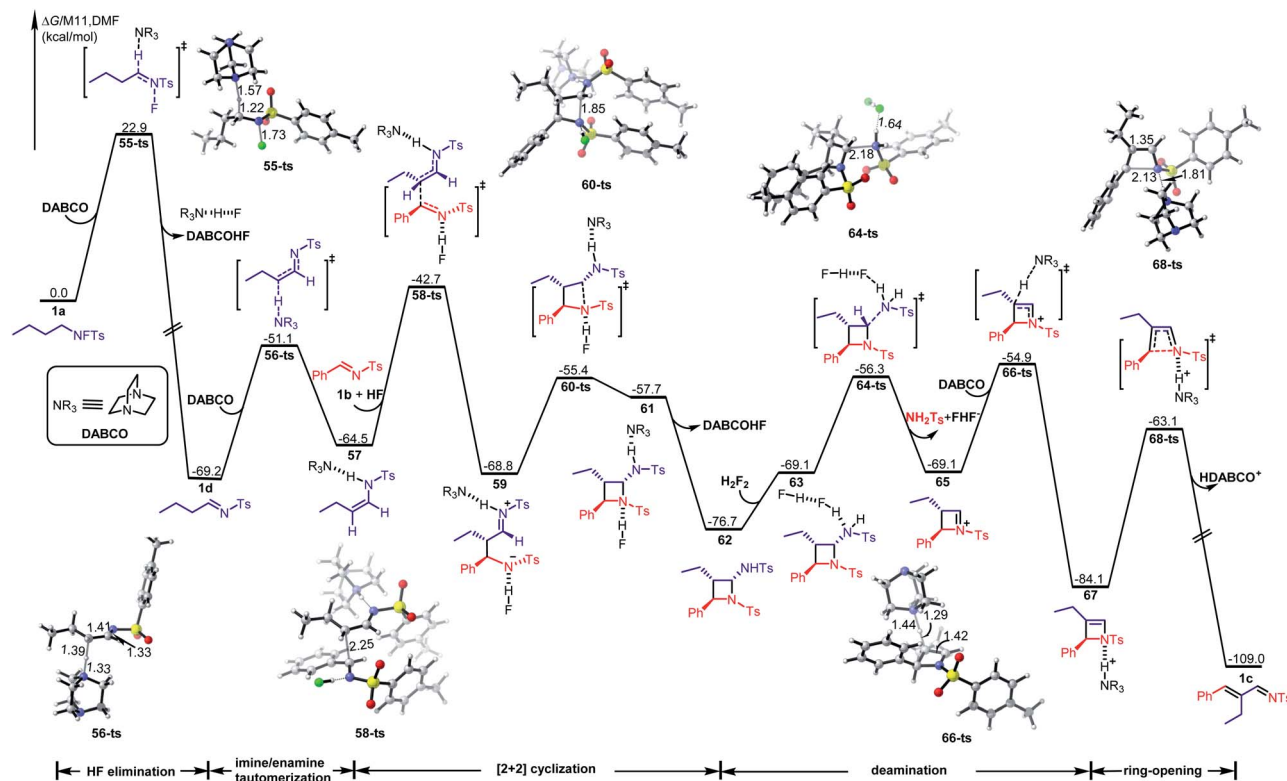
the free radical pathway was probably not involved (Scheme 5A). (2) When the reaction was carried out in the absence of **1b** under the standard reaction conditions, **52c** was formed through the self-coupling of **1a**, and no imine **1d** was detected (Scheme 5B). Next, the progress of the experiment was monitored by GC-MS; we detected the formation of the corresponding imine **1e** with **29a** as the substrate (Scheme 5C). Furthermore, control experiment using *N*-tosylimine **1d** instead of the *N*-fluoro sulfonamides also resulted in the formation of the desired product with Et₃N·HF as a promoter (Schemes 5D and E). On the other hand, when using *N*-chloro sulfonamide **1f** instead of the *N*-fluoro sulfonamides, no desired product was obtained. These observations illustrated that the imine may be a key intermediate and the fluorine atom was a necessary driving force for this C–H functionalization (Scheme 5F). (3) To rule out the possibility of the involvement of the classical aldol condensation reaction, we carried out cross-over experiments by addition of an external aldehyde. The corresponding imine with the aldehyde fragment was not detected (Schemes 5G and H). (4) To gain deeper insights into the mechanism, **30a–35a** with different substituents were treated with **1b** under our conditions, and the same product **1c** was obtained in good yields (Scheme 5I). More excitingly, using **25b** as the substrate instead of **1b**, **54c** was formed in 71% yield in this system (Scheme 5J). These results suggest that the sulfonamide substituent of the product (c) should be derived from the arylimine substrate (b). And a possible rearrangement process is proposed as shown in Scheme 5K.

To further reveal the details of this transformation, we performed a detailed DFT investigation. The calculated free energy

profile of the favored path is shown in Scheme 6 (the detailed information on the other paths is given in the ESI†). The reaction starts with a base-assisted HF elimination from *N*-fluorotorsylamide **1a** via transition state **55-ts** with an energy barrier of 22.9 kcal mol^{−1}, while (*E*)-imine **1d** is generated irreversibly with an exergonic 69.2 kcal mol^{−1}. Then an imine/enamine tautomerization³⁸ takes place via transition state **56-ts** with an energy barrier of 18.1 kcal mol^{−1} in the presence of DABCO to afford a hydrogen bond complex **57**. Enamine **57** serves as a nucleophile, which can react with arylimine **1b** through an intermolecular nucleophilic attack³⁹ via transition state **58-ts** to form a new C–C covalent bond. Interestingly, the nucleophile **57** is activated by the formation of a hydrogen bond with DABCO as well as the electrophilic partner imine **1b** is activated by another hydrogen bond formation with HF. Concomitantly, the generated zwitterionic intermediate **59** is stabilized by two hydrogen bonds with DABCO and HF, respectively. The overall activation free energy for this step is 26.5 kcal mol^{−1}, which would be considered as the rate limiting step in the whole pathway. When zwitterionic intermediate **59** is formed, an intramolecular nucleophilic addition can occur via transition state **60-ts** with an energy barrier of 13.4 kcal mol^{−1} to achieve the stepwise [2 + 2] cycloaddition. After the release of DABCO and HF, an azetidine intermediate **62** is generated reversibly. Intermediate **62** also exhibits amine characteristics, and therefore, a Brønsted acid assisted deamination can occur via transition state **64-ts** with an energy barrier of 20.4 kcal mol^{−1} in the presence of HF. The generated iminium intermediate **65** can be further deprotonated by DABCO via transition state **66-ts** to form the



Scheme 5 Mechanistic studies of the metal-free C–H functionalization strategy. (A–J) control experiments; (K) a possible reaction pathway.



Scheme 6 DFT calculations for the reaction of **1a** with **1b** at the M11/6-311+G(d,p)/SMD//B3LYP-D3/6-31+G(d)/SMD level of theory. The energies are in kcal mol⁻¹ and represent the relative free energies in DMF. The bond distances are in angstroms.

corresponding enamine intermediate **67**. The ring strain of that intermediate results in a 4π -electrocyclic ring-opening process *via* transition state **68-ts** to afford product **1c**. To summarise, the ring-closing/ring-opening rearrangement of *N*-fluorotosylamide with aldimines is constituted by base-assisted HF elimination to an imine, base-assisted imine/enamine tautomerization, step-wise [2 + 2] cyclization to generate azetidine, Brønsted acid prompted deamination of the aminal moiety, and deprotonated ring-opening.

Conclusions

In summary, we have developed a robust system that is capable of the cross-coupling of *N*-fluoro sulfonamides and arylimines without the need to use metals and oxidants, giving a series of α,β -unsaturated imines. This transformation showed exceptional functional group tolerance, high efficiency, and excellent chemoselectivity. More importantly, control experiments and DFT calculations indicate that the process involved ring-closing/ring-opening reorganization. We envision that this methodology will not only open up new avenues for synthesizing complex bioactive molecules but also inspire the discovery of more novel rearrangement systems.

Author contributions

J. H. conceived the project and directed the research. Y. L. and T.-P. L. supervised the mechanistic study. J. H. and T.-P. L. wrote

the paper. S. S., X. Y. and B. C. performed the experiments. X. L. performed the DFT calculations.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We are grateful for the financial support from the National Natural Science Foundation of China (21901114), the Natural Science Foundation of Jiangsu Province (BK20180685), the Natural Science Foundation of Jiangsu Provincial Department of Education (18KJB150017), and the Start-up Grant from Nanjing Tech University (38274017102 and 39837101). The SICAM Fellowship from the Jiangsu National Synergistic Innovation Center for Advanced Materials is also acknowledged.

Notes and references

- (a) K. R. Campos, *Chem. Soc. Rev.*, 2007, **36**, 1069–1084; (b) D. Seidel, *Acc. Chem. Res.*, 2015, **48**, 317–328; (c) J. W. Beatty and C. R. J. Stephenson, *Acc. Chem. Res.*, 2015, **48**, 1474–1484.
- (a) H. Jiang, J. He, T. Liu and J.-Q. Yu, *J. Am. Chem. Soc.*, 2016, **138**, 2055–2059; (b) Y. Wu, Y.-Q. Chen, T. Liu, M. D. Eastgate and J.-Q. Yu, *J. Am. Chem. Soc.*, 2016, **138**, 2055–2059; (c) Y.-Q. Chen, Z. Wang, Y. Wu, S. R. Wisniewski, J. X. Qiao,



- W. R. Ewing, M. D. Eastgate and J.-Q. Yu, *J. Am. Chem. Soc.*, 2018, **140**, 17884–17894; (d) Y.-Q. Chen, S. Singh, Y. Wu, Z. Wang, W. Hao, P. Verma, J. X. Qiao, R. B. Sunoj and J.-Q. Yu, *J. Am. Chem. Soc.*, 2020, **142**, 9966–9974.
- 3 (a) Z. Li, Q. Wang and J. Zhu, *Angew. Chem., Int. Ed.*, 2018, **57**, 13288–13292; (b) Z. Liu, H. Xiao, B. Zhang, H. Shen, L. Zhu and C. Li, *Angew. Chem., Int. Ed.*, 2019, **58**, 2510–2513; (c) A. Modak, E. N. Pinter and S. P. Cook, *J. Am. Chem. Soc.*, 2019, **141**, 18405–18410; (d) D. Bafaluy, H. Munoz-Molina, I. Funes-Ardoiz, S. Herold, A. J. D. Aguirre, H. Zhang, F. Maseras, T. R. Belderrain, P. J. Perez and K. Muniz, *Angew. Chem., Int. Ed.*, 2019, **58**, 8912–8916; (e) Y. Qin, Y. Han, Y. Tang, J. Wei and M. Yang, *Chem. Sci.*, 2020, **11**, 1276–1282.
- 4 (a) L. I. Willems and A. P. IJzerman, *Med. Res. Rev.*, 2010, **30**, 778–817; (b) L. Jia, R. D. Simpson, J. Yuan, Z. Xu, W. Zhao, S. Cacatian, C. M. Tice, J. Guo, A. Ishchenko, S. B. Singh, Z. Wu, B. M. McKeever, Y. Bukhtiyarov, J. A. Johnson, C. P. Doe, R. K. Harrison, G. M. McGeehan, L. W. Dillard, J. J. Baldwin and D. A. Claremon, *ACS Med. Chem. Lett.*, 2011, **2**, 747–751.
- 5 (a) J. He, S. Li, Y. Deng, H. Fu, B. N. Laforteza, J. E. Spangler, A. Homs and J.-Q. Yu, *Science*, 2014, **343**, 1216–1220; (b) S. Ye, W. Yang, T. Coon, D. Fanning, T. Neubert, D. Stamos and J.-Q. Yu, *Chem.-Eur. J.*, 2016, **22**, 4748–4752.
- 6 (a) B. F. V. Steijvoort, N. Kaval, A. A. Kulago and B. U. W. Maes, *ACS Catal.*, 2016, **6**, 4486–4490; (b) M. Maetani, J. Zoller, B. Melillo, O. Verho, N. Kato, J. Pu, E. Comer and S. L. Schreiber, *J. Am. Chem. Soc.*, 2017, **139**, 11300–11306; (c) D. Antermite, D. P. Affron and J. A. Bull, *Org. Lett.*, 2018, **20**, 3948–3952.
- 7 (a) B. Sundararaju, Z. Tang, M. Achard, G. V. M. Sharma, L. Toupet and C. Bruneau, *Adv. Synth. Catal.*, 2010, **352**, 3141–3146; (b) B. Sundararaju, M. Achard, G. V. M. Sharma and C. Bruneau, *J. Am. Chem. Soc.*, 2011, **133**, 10340–10343; (c) G.-Q. Xu, J.-T. Xu, Z.-T. Feng, H. Liang, Z.-Y. Wang, Y. Qin and P.-F. Xu, *Angew. Chem., Int. Ed.*, 2018, **130**, 5204–5208.
- 8 (a) B. Su, T. Lee and J. F. Hartwig, *J. Am. Chem. Soc.*, 2018, **140**, 18032–18038; (b) K. Yuan, F. Jiang, Z. Sahli, M. Achard, T. Roisnel and C. Bruneau, *Angew. Chem., Int. Ed.*, 2012, **124**, 9006–9010.
- 9 (a) A. Millet, P. Larini, E. Clot and O. Baudoin, *Chem. Sci.*, 2013, **4**, 2241–2247; (b) D. P. Affron, O. A. Davis and J. A. Bull, *Org. Lett.*, 2014, **16**, 4956–4959.
- 10 N. Takasu, K. Oisaki and M. Kanai, *Org. Lett.*, 2013, **15**, 1918–1921.
- 11 (a) X.-Z. Shu, X.-F. Xia, Y.-F. Yang, K.-G. Ji, X.-Y. Liu and Y.-M. Liang, *J. Org. Chem.*, 2009, **74**, 7464–7469; (b) R. J. Griffiths, W. C. Kong, S. A. Richards, G. A. Burley, M. C. Willis and E. P. A. Talbot, *Chem. Sci.*, 2018, **9**, 2295–2300; (c) Q. Gao, M. Wu, K. Zhang, N. Yang, M. Liu, J. Li, L. Fang, S. Bai and Y. Xu, *Org. Lett.*, 2020, **22**, 5645–5649.
- 12 L. Ma, A. Paul, M. Breugst and D. Seidela, *Chem.-Eur. J.*, 2016, **22**, 18179–18189.
- 13 W. Chen, Y. Kang, R. G. Wilde and D. Seidel, *Angew. Chem., Int. Ed.*, 2014, **53**, 5179–5182.
- 14 J. Zhang, S. Park and S. Chang, *J. Am. Chem. Soc.*, 2018, **140**, 13209–13213.
- 15 W. Chen, A. Paul, K. A. Abboud and D. Seidel, *Nat. Chem.*, 2020, **12**, 545–550.
- 16 (a) A. Noble and J. C. Anderson, *Chem. Rev.*, 2013, **113**, 2887–2939; (b) J. R. Hummel, J. A. Boerth and J. A. Ellman, *Chem. Rev.*, 2017, **117**, 9163–9227.
- 17 (a) R. M. Borzilleri, S. M. Weinreb and M. Parvez, *J. Am. Chem. Soc.*, 1995, **117**, 10905–10913; (b) J. Jin and S. M. Weinreb, *J. Am. Chem. Soc.*, 1997, **119**, 5773–5784; (c) O. Garcia-Mancheno, R. Gomez-Arrayas and J. C. Carretero, *J. Am. Chem. Soc.*, 2004, **126**, 456–457.
- 18 J. R. Hummel, J. A. Boerth and J. A. Ellman, *Chem. Rev.*, 2017, **117**, 9163–9227.
- 19 B. Eftekhari-Sis and M. Zirak, *Chem. Rev.*, 2017, **117**, 8326–8419.
- 20 (a) X. Yu, K. Chen, Q. Wang, S. Guo, S. Zha and J. Zhu, *Angew. Chem., Int. Ed.*, 2017, **56**, 5222–5226; (b) I. Chogii, P. Das, J. S. Fell, K. A. Scott, M. N. Crawford, K. N. Houk and J. T. Njardarson, *J. Am. Chem. Soc.*, 2017, **139**, 13141–13146; (c) C. L. Hugelshofer, V. Palani and R. Sarpong, *J. Am. Chem. Soc.*, 2019, **141**, 8431–8435; (d) D. F. Vargas, E. L. Larghi and T. S. Kaufman, *Nat. Prod. Rep.*, 2019, **36**, 354–401.
- 21 (a) G. K. S. Prakash, M. Mandal and G. A. Olah, *Org. Lett.*, 2001, **3**, 2847–2850; (b) K. Y. Lee, C. G. Lee and J. N. Kim, *Tetrahedron Lett.*, 2003, **44**, 1231–1234; (c) J. H. Babler, M. C. Atwood, J. E. Freaney and A. R. Vizslay, *Tetrahedron Lett.*, 2007, **48**, 7665–7667.
- 22 M. Largeron and M. B. Fleury, *Science*, 2013, **339**, 43–44.
- 23 V. Köhler, K. R. Bailey, A. Znabet, J. Raftery, M. Hel-liwell and N. J. Turner, *Angew. Chem., Int. Ed.*, 2010, **122**, 2228–2230.
- 24 D. Ghislieri, A. P. Green, M. Pontini, S. C. Willies, I. Rowles, A. Frank, G. Grogan and N. J. Turner, *J. Am. Chem. Soc.*, 2013, **135**, 10863–10869.
- 25 M. R. Chapman, S. C. Cosgrove, N. J. Turner, N. Kapur and A. J. Blacker, *Angew. Chem., Int. Ed.*, 2018, **57**, 10535–10539.
- 26 H. Yuan, W.-J. Yoo, H. Miyamura and S. Kobayashi, *J. Am. Chem. Soc.*, 2012, **134**, 13970–13973.
- 27 T. Sonobe, K. Oisaki and M. Kanai, *Chem. Sci.*, 2012, **3**, 3249–3255.
- 28 M. Largeron and M. B. Fleury, *Angew. Chem., Int. Ed.*, 2012, **51**, 5409–5412.
- 29 H. A. Ho, K. Manna and A. D. Sadow, *Angew. Chem., Int. Ed.*, 2012, **51**, 8607–8610.
- 30 M. L. Deb, S. S. Dey, I. Bento, M. T. Barros and C. D. Maycock, *Angew. Chem., Int. Ed.*, 2013, **125**, 9973–9977.
- 31 N. Li, X. Lang, W. Ma, H. Ji, C. Chen and J. Zhao, *Chem. Commun.*, 2013, **49**, 5034–5036.
- 32 X. Cui, W. Li, K. Junge, Z. Fei, M. Beller and P. J. Dyson, *Angew. Chem., Int. Ed.*, 2020, **59**, 7501–7507.
- 33 A. E. Wendlandt and S. S. Stahl, *Org. Lett.*, 2012, **14**, 2850–2853.
- 34 M. Rueping, C. Vila, A. Szadkowska, R. M. Koenigs and J. Fronert, *ACS Catal.*, 2012, **2**, 2810–2815.
- 35 (a) X. J. Lang, H. W. Ji, C. C. Chen, W. H. Ma and J. C. Zhao, *Angew. Chem., Int. Ed.*, 2011, **50**, 3934–3937; (b) X. J. Lang,



- W. H. Ma, Y. B. Zhao, C. C. Chen, H. W. Ji and J. C. Zhao, *Chem.-Eur. J.*, 2012, **18**, 2624–2631; (c) S. Naya, K. Kimura and H. Tada, *ACS Catal.*, 2012, **3**, 10–13.
- 36 K. Moriyama, M. Kuramochi, K. Fujii, T. Morita and H. Togo, *Angew. Chem., Int. Ed.*, 2016, **55**, 14546–14551.
- 37 (a) S. Mandal, S. Mahato and C. K. Jana, *Org. Lett.*, 2015, **17**, 3762–3765; (b) Y. Huang, H.-L. Fang, Y.-X. Huang, J. Sun and C.-G. Yan, *J. Org. Chem.*, 2019, **84**, 12437–12451.
- 38 X. Jie, Y. Shang, Z.-N. Chen, X. Zhang, W. Zhuang and W. Sun, *Nat. Commun.*, 2018, **9**, 5002–5011.
- 39 X. Bian, D. Zhang, Z. Huang and Y. Qin, *Synlett*, 2006, **20**, 3419–3422.

