Heterocycles

Deutsche Ausgabe: DOI: 10.1002/ange.201507122
Internationale Ausgabe: DOI: 10.1002/anie.201507122

Stereodivergent Synthesis of N-Heterocycles by Catalyst-Controlled, Activity-Directed Tandem Annulation of Diazo Compounds with Amino Alkynes

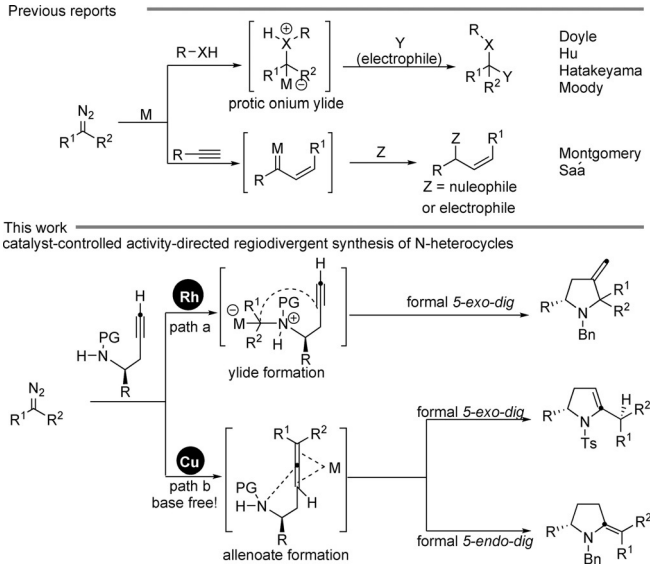
*Kai Liu, Chenghao Zhu, Junxiang Min, Shiyong Peng, Guangyang Xu, and Jiangtao Sun**

Dedicated to Professor Hongwen Hu on the occasion of his 90th birthday

Abstract: *A stereodivergent synthesis of five-membered N-heterocycles, such as 2,3-dihydropyrroles, and 2-methylene and 3-methylene pyrrolidines, has been developed through a tandem annulation of amino alkynes with diazo compounds and involves the trapping of in situ formed intermediates. Mechanistic investigations indicate that the copper-catalyzed tandem annulations proceed by allenoate formation and subsequent intramolecular hydroamination. In contrast, the rhodium-catalyzed protocol features a carbenoid insertion into the N–H bond and subsequent Conia-ene cyclization.*

The in situ trapping of an active intermediate, generated from diazo compounds with diverse functionality, by another nucleophile/electrophile has promoted the discovery of synthetically useful transformations, which allow rapid assembly of structurally complex molecules from readily available starting materials.[1] For example, by trapping the protic onium ylides, generated from metal carbenoid X–H insertions (X = N, O, S etc.), with different electrophiles, Hu and co-workers developed an array of novel multicomponent reactions for accessing polyfunctional molecules (Scheme 1).[2] Ni and Montgomery reported a [4+2+1] cycloaddition by nickel-catalyzed tandem vinyl nickel carbene formation and cyclization.[3] Saá and co-workers successively described novel cyclizations by trapping the vinyl ruthenium carbene intermediates generated in situ from alkyne and $TMSCHN_2$.[4] Very recently, Moody and co-workers reported the synthesis of highly substituted tetrahydrofurans by either a copper- or rhodium-catalyzed carbene O–H insertion/inramolecular aldol reaction sequence.[5] The high efficiency of this strategy and the ability to construct multiple bonds in one step has attracted considerable attention and resulted in the discovery of many novel transformations.[6]

Five-membered N-heterocycles, such as 2,3-dihydropyrroles, 2-methylene pyrrolidines, and 3-methylene pyrrolidines, are motifs found in numerous natural products, as well as in biologically active pharmaceuticals. However, preparation of such N-heterocyles generally requires diverse strategies from quite different starting materials.[7] Thus, a direct, controllable, and efficient synthetic method utilizing similar starting materials to selectively and divergently access such scaffolds is highly desirable. Herein, we describe a stereodivergent strategy by trapping in situ formed intermediates to construct diverse five-membered N-heterocycles in a single step.



Scheme 1. Strategies on in situ trapping of reaction intermediates. PG = protecting group.

In continuation of our interest in diazo-based carbene transfer,[8] we devised a catalyst-controlled, reactivity-directed tandem annulation to access different polysubstituted five-membered N-herterocylces. We anticipated that there are two possible pathways for the metal-catalyzed tandem reaction between diazo compounds and amino alkynes: 1) the prioritized metal-catalyzed N–H insertion could generate active ylide, which would then be trapped by the alkynyl moiety and undergo a formal *5-exo-dig* cyclization to give 3-methylene pyrrolidines; 2) the metal-catalyzed cross-coupling of an alkyne with diazo compounds could furnish allenoate intermediates as the first step, and they would then undergo either formal *5-exo-dig* or *5-endo-dig* intramolecular hydroamination to give the corresponding cycloaddition products (Scheme 1). Obviously, the challenges are controlling the

[*] K. Liu,[+] C. Zhu,[+] J. Min, Dr. S. Peng, G. Xu, Prof. Dr. J. Sun
School of Pharmaceutical Engineering & Life Science
Changzhou University
Changzhou 213164 (China)
E-mail: jtsun08@gmail.com

[+] These authors contributed equally to this work.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201507122.

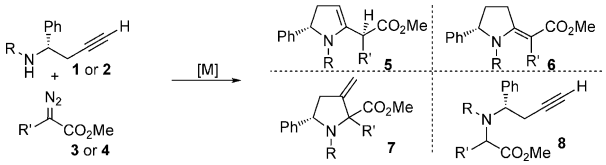
© 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

competitive ring-closing modes and avoiding reaction termination at either the first N–H insertion or cross-coupling stage.

Initially, the reaction of the chiral homopropargyl sulfonamide **1a** with phenyl diazoacetate (**3a**) was investigated (Table 1). Screening the reaction parameters indicated that the tandem annulation occurred in the presence of CuCl (10 mol%) in acetonitrile and provided 2,3-dihydropyrrole **5a** in 70% yield, with 4.3:1 d.r. and 97:3 e.r. (entry 3). Other copper(I) and copper(II) catalysts gave lower yields. Next, the reaction of the N-benzyl amino alkyne **2a** with **3a** was examined. With $CHCl_3$ as the solvent, (*E*)-**6a** was isolated in 82% yield with a 98:2 e.r. (entry 9). Other copper catalysts also gave (*E*)-**6a** in low to moderate yields. The tandem annulation of **2a** with **4a** proceeded smoothly to give the 3-methylene pyrrolidine **7a** as a single isomer in 78% yield and with 99:1 e.r. catalyzed by 3 mol% of $[Rh_2(esp)_2]$ and 10 mol% of $ZnCl_2$ in CH_2Cl_2 (entry 14).[9] The presence of $ZnCl_2$ was beneficial to the cyclization. By using 3 mol% of $[Rh_2(esp)_2]$ alone, **7a** was observed in 32% yield together with 26% yield of **8a** (entry 13). By using $In(OTf)_2$ instead of $ZnCl_2$, only the insertion product **8a** was isolated (entry 15). Also, reducing the catalyst loading led to low efficiency (entry 16). Other rhodium complexes were ineffective in this reaction. Notably, the $[Rh_2(esp)_2]$-catalyzed reaction of **2a** and **3a** gave the insertion product **8b** in 77% yield (entry 19). Furthermore, in the presence of 10 mol% of $ZnCl_2$, **7m** was isolated in 36% yield together with 22% yield of **8b** (entry 20).

Based on the above optimization (Table 1, entry 3), the substrate scope for the synthesis of 2,3-dihydropyrroles was investigated (Table 2). Generally, the chiral homopropargyl sulfonamides containing either electron-rich or electron-deficient aryl groups, adjacent to the N-atom, all gave the corresponding products in moderate to high yields and with good d.r. values. In particular, **5a** and **5b** were obtained in 97:3 e.r. and no obvious erosion of enantiopurity was observed. The thiophene- or furan-substituted chiral sulfonamides were also tolerated and gave the desired products (**5f**, **5g**, and **5n**) in moderate yield. The alkyl-substituted chiral sulfonamides also worked well and afforded the chiral dihydropyrrolidines in slightly lower yields compared with

Table 1: Optimization of the tandem annulations.[a,b,c]

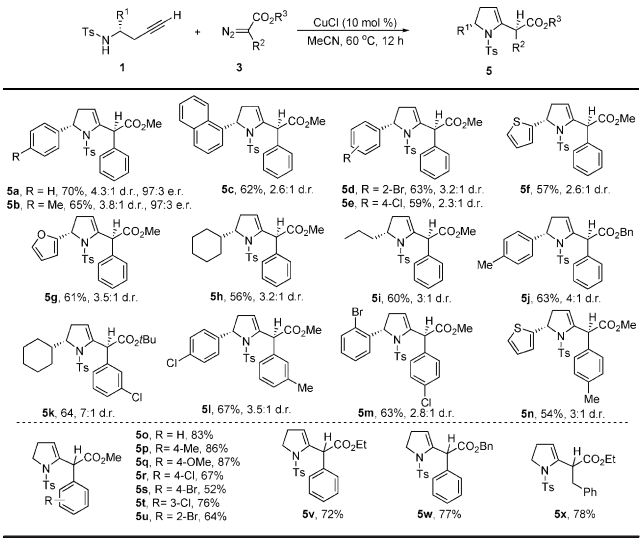


Entry	Catalyst	Alkyne	Diazo	Solvent	Yield [%] **5** (d.r., e.r.)	**6** (*E*/*Z*, e.r.)	**7** (e.r.)
1	CuI	**1a** (R = Ts)	**3a** (R′ = Ph)	MeCN	**5a**, 30 (2:1, 97:3)	0	0
2	CuBr	**1a**	**3a**	MeCN	**5a**, 47 (3:1, 97:3)	0	0
3	CuCl	**1a**	**3a**	MeCN	**5a**, 70 (4.3:1, 97:3)	0	0
4	$Cu(OTf)_2$	**1a**	**3a**	MeCN	–	–	–
5	$Cu(OAc)_2$	**1a**	**3a**	MeCN	**5a**, 29 (2.5:1, –)	0	0
6	$CuBr_2$	**1a**	**3a**	MeCN	**5a**, 26 (3:1, –)	0	0
7	CuI	**2a** (R = Bn)	**3a**	$CHCl_3$	0	**6a**, 45 (1:0, 97:3)	0
8	CuBr	**2a**	**3a**	$CHCl_3$	0	**6a**, 61 (1:0, 97:3)	0
9	CuCl	**2a**	**3a**	$CHCl_3$	0	**6a**, 82 (1:0, 98:2)	0
10	$Cu(OTf)_2$	**2a**	**3a**	$CHCl_3$	–	–	–
11	$Cu(OAc)_2$	**2a**	**3a**	$CHCl_3$	0	**6a**, 50 (1:0, 97:3)	0
12	$CuBr_2$	**2a**	**3a**	$CHCl_3$	0	**6a**, 23 (1:0)	0
13	$[Rh_2(esp)_2]$	**2a**	**4a** (R′ = CO_2Me)	CH_2Cl_2	0	0	**7a**, 32; **8a**, 26
14	$[Rh_2(esp)_2]/ZnCl_2$	**2a**	**4a**	CH_2Cl_2	0	0	**7a**, 78 (99:1)
15	$[Rh_2(esp)_2]/In(OTf)_3$	**2a**	**4a**	CH_2Cl_2	0	0	**7a**, < 5; **8a**, 72
16[d]	$[Rh_2(esp)_2]/ZnCl_2$	**2a**	**4a**	CH_2Cl_2	0	0	**7a**, 23
17	$[Rh_2(OAc)_4]/ZnCl_2$	**2a**	**4a**	CH_2Cl_2	–	–	–
18	$[\{Cp^*RhCl_2\}_2]/ZnCl_2$	**2a**	**4a**	CH_2Cl_2	–	–	–
19	$[Rh_2(esp)_2]$	**2a**	**3a**	CH_2Cl_2	0	0	**7m**, 0; **8b**, 77
20	$[Rh_2(esp)_2]/ZnCl_2$	**2a**	**3a**	CH_2Cl_2	0	0	**7m**, 36; **8b**, 22

[a] Reactions were carried out with either **1** or **2** reacting with either **3** or **4** (0.5 mmol), a copper salt (10 mol%) or rhodium catalyst (3 mol%), at 60°C. [b] Yield of the isolated single isomer. Reaction time: 12 h for entries 1 to 6; 18 h for entries 7 to 12; 8 h for entries 13 to 20. [c] The d.r. and *E*/*Z* values were determined by ^1H NMR analysis of the crude reaction mixture. The e.r. values were determined by HPLC analysis using a chiral stationary phase. [d] 1 mol% of $[Rh_2(esp)_2]$. Cp* = C_5Me_5, esp = α, α, α′, α′-tetramethyl-1,3-benzenedipropionic acid, Tf = trifluoromethanesulfonyl, Ts = 4-toluenesulfonyl.

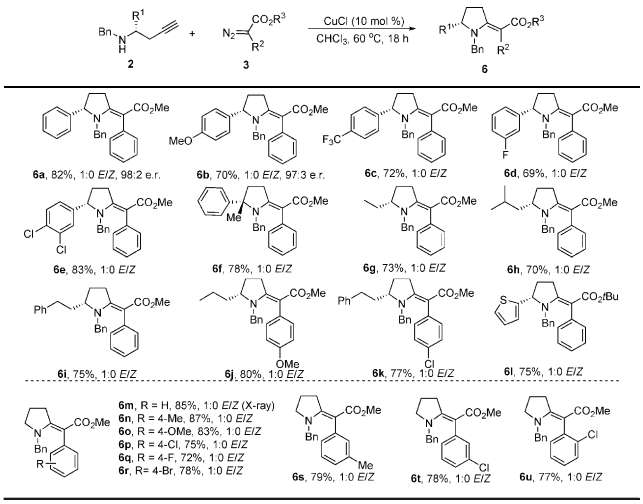
 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Table 2: Scope of copper-catalyzed tandem annulation towards dihydropyrroles.[a,b]



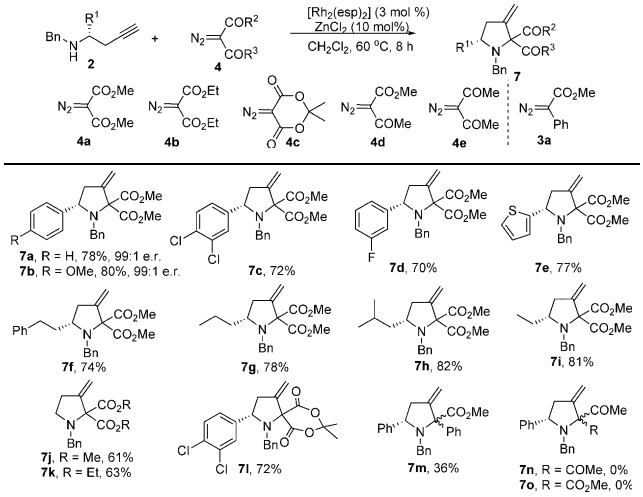
[a] Yield of the isolated single isomer. [b] The d.r. values were determined by ^{1}H NMR analysis of the crude reaction products. The e.r. values were determined by HPLC analysis using a chiral stationary phase.

Table 3: Scope of the copper-catalyzed tandem annulation towards pyrrolidines.[a,b]



[a] Yield of purified product. [b] *E*/*Z* was determined by ^{1}H NMR analysis of the crude reaction mixture. The e.r. values were determined by HPLC analysis using a chiral stationary phase.

Table 4: Scope for the rhodium-catalyzed tandem annulation.[a,b]



[a] Yield of purified product. [b] The e.r. values were determined by HPLC analysis using a chiral stationary phase.

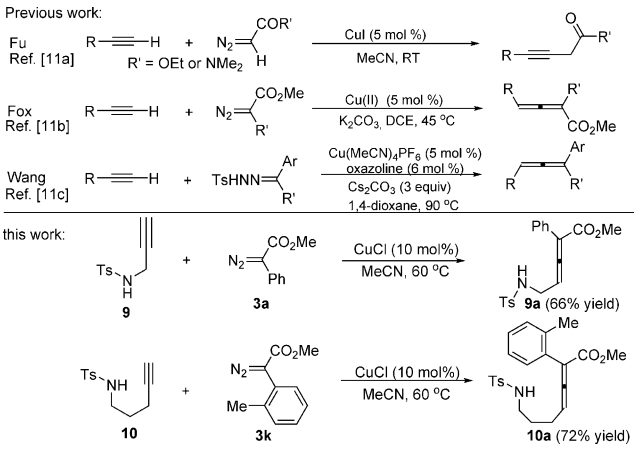
the aryl-substituted substrates. The major isomers had an *S*,*S* configuration, which was confirmed by the X-ray structure of **5b′** (diastereomer of **5b**).[10] Next, nonsubstituted homopropargyl sulfonamides were also examined. Comparatively, electron-rich phenyl diazoacetates gave the cyclization products in higher yields than the electron-poor ones. Notably, benzyl diazoacetate was also tolerated and delivered **5x** in 78% yield.

Next, the copper-catalyzed tandem reaction of the diazo compounds **3** with **2** to provide pyrrolidines (**6**) was further performed under the optimal reaction conditions (Table 1, entry 9) (Table 3). The (*S*)-*N*-benzyl-but-3-yn-1-amines **2** containing either electron-rich or electron-poor phenyl groups adjacent to the N-atom gave the corresponding chiral pyrrolidines in moderate to high yields. Among them, **6a** and **6b** were isolated in 82 and 70% yield, respectively, with the corresponding e.r. values of 98:2 and 97:3 e.r. The chiral alkyl- and thiophene-substituted *N*-benzyl but-3-yn-1-amines also worked well in this reaction (**6g–l**). A structurally hindered *N*-benzyl amino alkyne was tolerated and gave **6f** in 78% yield. It is noteworthy that the products with an *E* configuration were all favored, and was confirmed by X-ray structure of **6m**.[10]

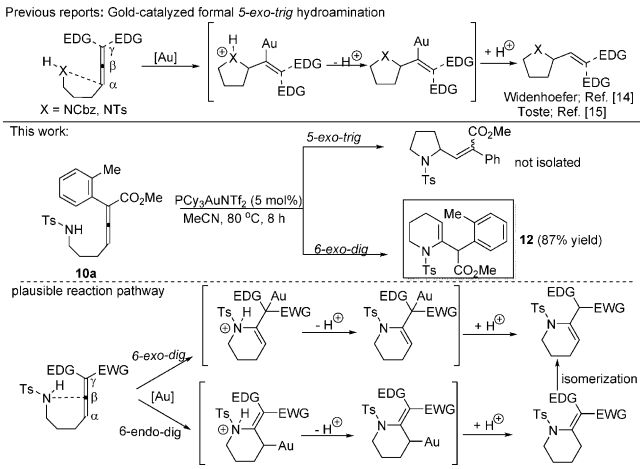
The substrate scope and the limitations of the rhodium-catalyzed 3-methylenepyrrolidine formation with a range of acceptor/acceptor diazo substrates was further investigated (Table 4). The reaction between **2** and the diazocarboxylate **4a** proceeded smoothly to furnish the corresponding 3-methylene pyrrolidines in moderate to high yields and with well-maintained optical purity (99:1 e.r. for **7a** and **7b**). Other dicarbonyl diazo compounds were also examined. The diazoesters **4b** and **4c** were well-tolerated and delivered **7k** and **7l** in high yields. However, reactions between **2** and either the diazoketone **4d** or **4e** were sluggish and the desired products (**7n** and **7o**) were not obtained, probably owing to the inert N–H insertion step for these two substrates.

To gain insight into the reaction mechanism, further investigations were performed. In 2004, Suárez and Fu reported that, under nonbasic conditions, copper-catalyzed coupling of terminal alkynes with diazo compounds selectively afforded 3-alkynoates.[11a] Later, the groups of Fox[11b] and Wang[11c] successively described that the presence of a base is essential for the highly efficient allene/allenoate formation. Since the reaction of **1** with **3** gave the 2,3-dihydropyrroles directly and the reaction intermediates cannot be isolated, we performed the reaction of alkynes **9** and **10** with **3a** and **3k**, respectively (Scheme 2). Under the same reaction conditions as used for the reactions in Table 2, the allenoates **9a** and **10a** were isolated in 66 and 72% yield,

© 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim



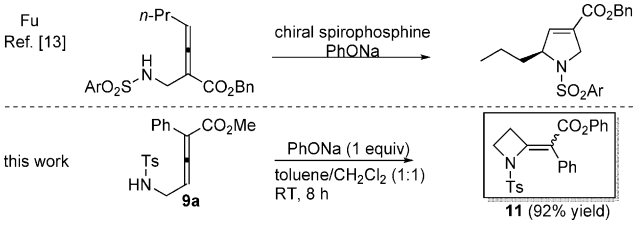
Scheme 2. Copper-catalyzed cross-coupling of alkynes with diazo compounds.



Scheme 4. Gold-catalyzed cyclization of allene/allenoate. EDG = electron-donation groups, EWG = electron-withdrawing group.

respectively. These experiments disclosed that, different from former reports, even in the absence of a base the allenoates were also obtained as the major products for the simple copper-catalyzed cross-coupling of diazoacetates with alkynyl sulfonamides.[12] These experiments also provided strong evidence that the copper-catalyzed tandem annulation of **1** with **3** probably proceeded via an allenoate intermediate.

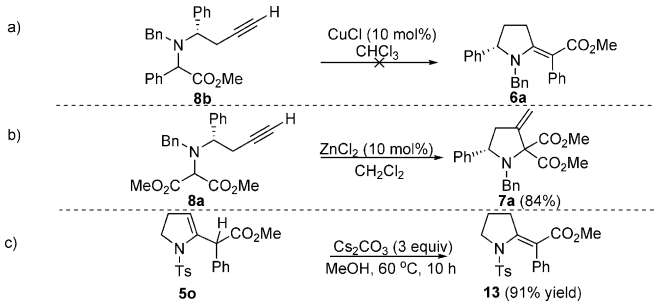
In a recent report, Kramer and Fu found that treatment of an allene with a phosphine ligand and PhONa furnished 2,5-dihydropyrrole as a single product (Scheme 3).[13] In contrast, we found that, after treatment of **9a** with one equivalent of PhONa, the azetidine **11** was obtained in high yield with or without the addition of a phosphine ligand.



Scheme 3. Cylization of sulfonamide allene/allenoate.

Previously, the groups of Widenhoefer[14] and Toste[15] reported that allenes bearing alkyl substituent(s) at the γ-position can undergo gold(I)-catalyzed intramolecular hydroamination at the α-position to produce 2-vinylpyrrolidines (Scheme 4). We found that, in the presence of 5 mol% of PCy_3AuNTf_2, the intramolecular hydroamination of the allenoate **10a** occurred smoothly to deliver the *N*-tosyl tetrahydropyridine **12** in 87% yield.[10] The former reports and our observations indicate that the substituents on allenes play a vital role in the ring-closing mode. If an electron-withdrawing group is present in the γ-position, the intramolecular hydroamination would occur at the β-position and proceed by formal 6-*exo-dig* or *6-endo-dig* cyclization/isomerization to give tetrahydropyridine as final product.

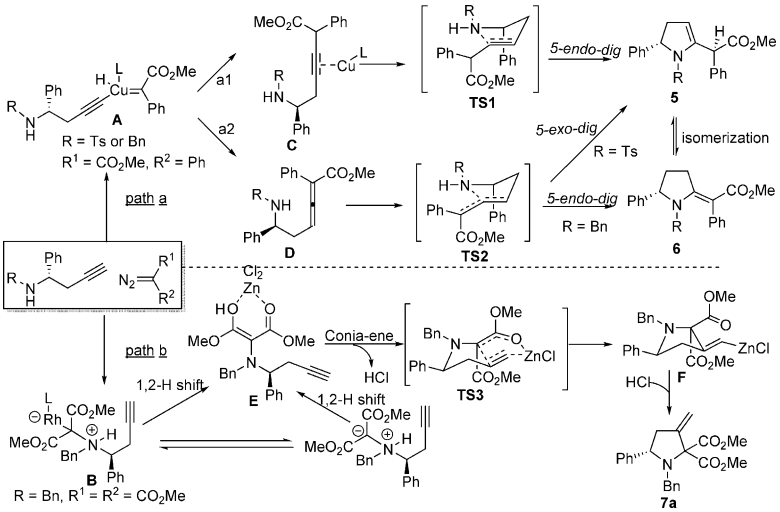
Next, additional control experiments were carried out to help understand the mechanism. Treatment of **8b** with CuCl under standard reaction conditions given in Table 2 did not afford **6a**, and thus indicated that the formation of pyrrolidines (**6**) does not proceed by tandem N–H insertion/cyclization, but by the prioritized coupling of alkyne with diazo compounds (Scheme 5a). Furthermore, after treatment of **8a** with 10 mol% of $ZnCl_2$, **7a** was obtained in 84% yield, thus suggesting that $ZnCl_2$ could promote the Conia-ene reaction (Scheme 5b).[16] When **5o** was subjected to 3 equivalents of Cs_2CO_3, the double bond was isomerized to give a product with an exocyclic double bond (**13**) in 91% yield (Scheme 5c).



Scheme 5. Control experiments.

Plausible mechanisms for different annulations have been proposed (Scheme 6). The reaction of the the homopropargyl amine with donor/acceptor diazoacetate **3a** in the presence of CuCl generates the intermediate **A**, which might provide the alkyne intermediate **C** by path a1. A formal *5-endo-dig* cyclization then proceeds through **TS1** (TS = transition state) to afford **5**. Alternatively, the generation of the allenoate intermediate **D** is most likely preferred, and would undergo either formal *5-exo-dig* or *5-endo-dig* cycloaddition via **TS2** to give either **5** or **6**, respectively. Experimental results show that *N*-tosyl amino alkynes are more likely to form **5**, while for *N*-benzyl amino alkynes, **6** would be

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim



Scheme 6. Proposed reaction mechanisms.

more stable. This reactivity was indirectly proven by a control experiment (Scheme 5c). For rhodium-catalyzed annulation, the reaction of **2a** with **4a** generates the ylide **B**, and a subsequent 1,2-H shift affords the insertion product **E** (Scheme 6). Next, $ZnCl_2$-initiated Conia-ene reaction via **TS3** provides **7a** as the final product.

In summary, a regiodivergent synthesis of five-membered N-heterocycles has been developed by trapping the in situ formed intermediates through a metal-catalyzed tandem annulation of amino alkynes and diazo compounds. Mechanistic investigations indicate that the copper-catalyzed tandem annulations proceeded by allenoate formation and subsequent intramolecular hydroamination. On the contrary, the rhodium-catalyzed protocol features a carbenoid insertion into the N–H bond followed by a Conia-ene reaction. Furthermore, we also presented here the base-free copper-catalyzed allenoate formation from diazo compounds. The intramolecular hydroamination of amino allenoates gave different cyclization products compared with those described in previous reports.

Acknowledgements

This project is supported by NSFC (No. 21172023), the Priority Academic Program Development of Jiangsu Higher Education Institution (PAPD), and Jiangsu Key Laboratory of Advanced Catalytic Materials and Technology (BM2012110).

Keywords: copper · cyclizations · diazo compounds · homogeneous catalysis · rhodium

How to cite: *Angew. Chem. Int. Ed.* **2015**, *54*, 12962–12967
Angew. Chem. **2015**, *127*, 13154–13159

[1] For reviews, see: a) X. Guo, W. Hu, *Acc. Chem. Res.* **2013**, *46*, 2427; b) D. Xing, W. Hu, *Tetrahedron Lett.* **2014**, *55*, 777.

[2] For selected recent examples, see: a) D. Zhang, H. Qiu, L. Jiang, F. Lv, C. Ma, W. Hu, *Angew. Chem. Int. Ed.* **2013**, *52*, 13356; *Angew. Chem.* **2013**, *125*, 13598; b) X. Guo, W. Liu, W. Hu, *Chem. Asian J.* **2014**, *9*, 117; c) C. Jiang, D. Xing, W. Hu, *Chem. Commun.* **2014**, *50*, 951; d) J. Jiang, X. Ma, C. Ji, Z. Guo, T. Shi, S. Liu, W. Hu, *Chem. Eur. J.* **2014**, *20*, 1505; e) S. Jia, D. Xing, D. Zhang, W. Hu, *Angew. Chem. Int. Ed.* **2014**, *53*, 13098; *Angew. Chem.* **2014**, *126*, 13314; f) X. Ma, J. Jiang, S. Lv, W. Yao, Y. Yang, S. Liu, F. Xia, W. Hu, *Angew. Chem. Int. Ed.* **2014**, *53*, 13136; *Angew. Chem.* **2014**, *126*, 13352; g) D. Zhang, J. Zhou, F. Xia, Z. Kang, W. Hu, *Nat. Commun.* **2015**, *6*, 5801; h) M. Tang, D. Xing, H. Huang, W. Hu, *Chem. Commun.* **2015**, *51*, 10612; i) Y. Qian, X. Xu, X. Wang, P. J. Zavalij, W. Hu, M. P. Doyle, *Angew. Chem. Int. Ed.* **2012**, *51*, 5900; *Angew. Chem.* **2012**, *124*, 6002.

[3] a) Y. Ni, J. Montgomery, *J. Am. Chem. Soc.* **2004**, *126*, 11162; b) Y. Ni, J. Montgomery, *J. Am. Chem. Soc.* **2006**, *128*, 2609.

[4] a) F. Cambeiro, S. López, J. A. Varela, C. Saá, *Angew. Chem. Int. Ed.* **2012**, *51*, 723; *Angew. Chem.* **2012**, *124*, 747; b) F. Cambeiro, S. López, J. A. Varela, C. Saá, *Angew. Chem. Int. Ed.* **2014**, *53*, 5959; *Angew. Chem.* **2014**, *126*, 6069; c) C. González-Rodríguez, J. R. Suárez, J. A. Varela, C. Saá, *Angew. Chem. Int. Ed.* **2015**, *54*, 2724; *Angew. Chem.* **2015**, *127*, 2762.

[5] S. M. Nicolle, W. Lewis, C. J. Hayes, C. J. Moody, *Angew. Chem. Int. Ed.* **2015**, *54*, 8485; *Angew. Chem.* **2015**, *127*, 8605.

[6] For selected recent examples, see: a) Z. Zhang, Y. Liu, M. Gong, X. Zhao, Y. Zhang, J. Wang, *Angew. Chem. Int. Ed.* **2010**, *49*, 1139; *Angew. Chem.* **2010**, *122*, 1157; b) Y.-T. Tosi, Z. Zhou, W.-Y. Yu, *Org. Lett.* **2011**, *13*, 5370; c) C.-Y. Zhou, J.-C. Wang, J. Wei, Z.-J. Xu, Z. Guo, K.-H. Low, C.-M. Che, *Angew. Chem. Int. Ed.* **2012**, *51*, 11376; *Angew. Chem.* **2012**, *124*, 11538; d) S. S. So, A. E. Mattson, *J. Am. Chem. Soc.* **2012**, *134*, 8798; e) T. J. Auvil, S. S. So, A. E. Mattson, *Angew. Chem. Int. Ed.* **2013**, *52*, 11317; *Angew. Chem.* **2013**, *125*, 11527; f) Q. Xiao, B. Wang, L. Tian, Y. Yang, J. Ma, Y. Zhang, S. Chen, J. Wang, *Angew. Chem. Int. Ed.* **2013**, *52*, 9305; *Angew. Chem.* **2013**, *125*, 9475; g) Y. Hashimoto, K. Itoh, A. Kakehi, M. Shiro, H. Suga, *J. Org. Chem.* **2013**, *78*, 6182; h) A. R. Reddy, C.-Y. Zhou, C.-M. Che, *Org. Lett.* **2014**, *16*, 1048; i) N. D. Paul, S. Mandal, M. Otte, X. Cui, X. P. Zhang, B. de Bruin, *J. Am. Chem. Soc.* **2014**, *136*, 1090; j) D.-F. Chen, F. Zhao, Y. Hu, L.-Z. Gong, *Angew. Chem. Int. Ed.* **2014**, *53*, 10763; *Angew. Chem.* **2014**, *126*, 10939; k) F.-N. Ng, Y.-F. Lau, Z. Zhou, W.-Y. Yu, *Org. Lett.* **2015**, *17*, 1676; l) F. Ye, S. Qu, L. Zhou, C. Peng, C. Wang, J. Cheng, M. L. Hossain, Y. Liu, Y. Zhang, Z.-X. Wang, J. Wang, *J. Am. Chem. Soc.* **2015**, *137*, 4435; m) M.-Y. Wu, W.-W. He, X.-Y. Liu, B. Tan, *Angew. Chem. Int. Ed.* **2015**, *54*, 9409; *Angew. Chem.* **2015**, *127*, 9541; n) Y. Xia, S. Feng, Z. Liu, Y. Zhang, J. Wang, *Angew. Chem. Int. Ed.* **2015**, *54*, 7891; *Angew. Chem.* **2015**, *127*, 8002.

[7] For selected examples, see: a) Y. Ni, R. M. Kassab, M. V. Chevliakov, J. Montgomery, *J. Am. Chem. Soc.* **2009**, *131*, 17714; b) A. R. Reddy, C.-Y. Zhou, Z. Guo, J. Wei, C.-M. Che, *Angew. Chem. Int. Ed.* **2014**, *53*, 14175; *Angew. Chem.* **2014**, *126*, 14399; c) S. Ma, W. Gao, *Org. Lett.* **2002**, *4*, 2989; d) C. C. Scarborough, S. S. Stahl, *Org. Lett.* **2006**, *8*, 3251; e) Y.-F. Yu, C. Shu, B. Zhou, J.-Q. Li, J.-M. Zhou, L.-W. Ye, *Chem. Commun.* **2015**, *51*, 2126; f) Y. Xia, X. Liu, H. Zheng, L. Lin, X. Feng, *Angew. Chem. Int. Ed.* **2015**, *54*, 227; *Angew. Chem.* **2015**, *127*, 229.

[8] a) G. Liu, G. Xu, J. Li, D. Ding, J. Sun, *Org. Biomol. Chem.* **2014**, *12*, 1387; b) D. Ding, X. Lv, J. Li, G. Xu, B. Ma, J. Sun, *Chem. Asian J.* **2014**, *9*, 1539; c) D. Zhang, G. Xu, D. Ding, C. Zhu, J. Li,

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

J. Sun, *Angew. Chem. Int. Ed.* **2014**, *53*, 11070; *Angew. Chem.* **2014**, *126*, 11250; d) G. Xu, C. Zhu, W. Gu, J. Li, J. Sun, *Angew. Chem. Int. Ed.* **2015**, *54*, 883; *Angew. Chem.* **2015**, *127*, 897; e) L. Qiu, D. Huang, G. Xu, Z. Dai, J. Sun, *Org. Lett.* **2015**, *17*, 1810; f) C. Zhu, G. Xu, K. Liu, L. Qiu, S. Peng, J. Sun, *Chem. Commun.* **2015**, *51*, 12768.

[9] A modified procedure was reported by Hatakeyama et al.: F. Urabe, S. Miyamoto, K. Takahashi, J. Ishihara, S. Hatakeyama, *Org. Lett.* **2014**, *16*, 1004.

[10] See the Supporting Information for the X-ray structures of **5b′**, **6m**, and **12**. CCDC 1415440 (**5b′**), 1415441 (**6m**), and 1415442 (**12**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

[11] a) A. Suárez, G. C. Fu, *Angew. Chem. Int. Ed.* **2004**, *43*, 3580; *Angew. Chem.* **2004**, *116*, 3664; b) M. Hassink, X. Liu, J. M. Fox, *Org. Lett.* **2011**, *13*, 2388; c) Q. Xiao, Y. Xia, H. Li, Y. Zhang, J. Wang, *Angew. Chem. Int. Ed.* **2011**, *50*, 1114; *Angew. Chem.* **2011**, *123*, 1146; d) J.-S. Poh, D. N. Tran, C. Battilocchio, J. M. Hawkins, S. V. Ley, *Angew. Chem. Int. Ed.* **2015**, *54*, 7920; *Angew. Chem.* **2015**, *127*, 8031.

[12] During preparation of this manuscript, Liu and co-workers reported the synthesis of chiral allenoates from terminal alkynes and diazoaceates in the presence of chiral guanidinium salts: Y. Tang, Q. Chen, X. Liu, G. Wang, L. Lin, X. Feng, *Angew. Chem. Int. Ed.* **2015**, *54*, 9512; *Angew. Chem.* **2015**, *127*, 9648.

[13] S. Kramer, G. C. Fu, *J. Am. Chem. Soc.* **2015**, *137*, 3803.

[14] a) Z. Zhang, C. Liu, R. E. Kinder, X. Han, H. Qian, R. A. Widenhoefer, *J. Am. Chem. Soc.* **2006**, *128*, 9066; b) Z. Zhang, C. F. Bender, R. A. Widenhoefer, *J. Am. Chem. Soc.* **2007**, *129*, 14148.

[15] R. L. LaLonde, B. D. Sherry, E. J. Kang, F. D. Toste, *J. Am. Chem. Soc.* **2007**, *129*, 2452.

[16] a) M. A. Boaventura, J. Drouin, J. M. Conia, *Synthesis* **1983**, 8014; b) W. Hess, J. W. Burton, *Adv. Synth. Catal.* **2011**, *353*, 2966.

Received: July 31, 2015
Published online: September 9, 2015

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim