

Synthesis of 1,2,3-Trisubstituted Indolizines, Pyrrolo[1,2-*a*]quinolines, and Pyrrolo[2,1-*a*]isoquinolines from 1,2-Allenyl Ketones

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Keywords: Allenes / Ketones / Multicomponent reactions / Nitrogen heterocycles

An efficient synthesis of substituted indolizine and its benzo derivatives, pyrrolo[1,2-*a*]quinolines and pyrrolo[2,1-*a*]isoquinolines, by the reaction of allenyl ketones with α -bromo carbonyl compounds and pyridines (quinoline or isoquinoline) under mild conditions without an added oxidant other

than molecular oxygen from air was developed. Notably, allenyl ketones with or without a substituent attached to the internal position of the allene moiety afforded indolizine derivatives with different substitution patterns.

Introduction

As an important class of N-bridgehead bicyclic ring systems, indolizine and its benzo derivatives, pyrrolo[1,2-*a*]quinolines and pyrrolo[2,1-*a*]isoquinolines, have received much attention owing to their unique electronic structure, interesting biological activities, and broad pharmaceutical applications.^[1–3] Because of their importance, considerable efforts have been made to the development of new methods to synthesize indolizine derivatives. As a result, a number of processes including the cycloaddition of pyridinium, quinolinium, and isoquinolinium ylides with alkene and alkyne dipolarophiles;^[3–8] difunctionalization of naphthoquinone,^[9] iodine-promoted cascade reaction of methyl ketone with pyridine,^[10] copper-catalyzed cycloisomerization of 2-pyridylpropargylic acetates;^[11] organocopper-mediated cross-coupling/cycloisomerization of 2-pyridylpropargylic mesylates;^[12] elaboration of pyranoquinolines through site-selective electrophilic cyclization and subsequent opening of the pyran ring^[13] have been developed. Although these protocols are generally reliable, there are still some difficulties and limitations, especially if less reactive alkene dipolarophiles are used as substrates. To obtain reasonable yields, difunctionalized alkenes such as fluoriodoalkenes, fluorinated vinyl tosylates, and dichloro- α,β -unsaturated ketones have to be used. Otherwise, an added oxidant such as MnO₂ or 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ), should be used for the dehydrogenative aromatiza-

tion of the in situ formed tetrahydroindolizines. Moreover, for monofunctionalized alkenes, self-condensation of the pyridinium salt with its enol form often takes place to give undesired products.

As part of our research interest in exploring allene derivatives as versatile synthetic intermediates,^[14] we hypothesized that a more efficient and practical synthesis of indolizine derivatives without the use of an added oxidant might be achieved by using allenyl ketones as the required olefinic dipolarophiles, as they are highly reactive as nucleophilic addition acceptors and have been frequently used as a powerful tool in forming carbon–carbon and carbon–heteroatom bonds.^[15,16] Herein we wish to report our preliminary results in this regard.

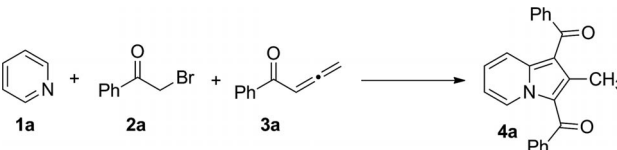
Results and Discussion

To check the feasibility of our envisioned synthesis of indolizine from allenyl ketones, the reaction of pyridine (**1a**; 0.5 mmol) and 2-bromo-1-phenylethanone (**2a**; 0.5 mmol) with 1-phenylbuta-2,3-dien-1-one (**3a**; 0.5 mmol) was first studied. To our delight, stirring of a mixture of **1a**, **2a**, and **3a** in refluxing CH₃CN in the presence of Na₂CO₃ (0.1 equiv.) for 6 h afforded the desired (2-methylindolizine-1,3-diyl)bis(phenylmethanone) (**4a**) in 35% yield (Table 1, Entry 1). Inspired by this result, the reaction was thoroughly optimized in terms of different amounts of Na₂CO₃, various bases, solvents, as well as reaction temperatures (Table 1, Entries 2–16). It turned out that a yield of 73% could be obtained if the reaction was run in refluxing CH₃CN in the presence of K₂CO₃ (1 equiv.) for 2 h (Table 1, entry 6).

With the optimized conditions in hand, we then studied the scope and generality of this new reaction. First, 1,2-allenyl ketones **3** were treated with **1a** and **2a**. The results in Table 2 show that the R³ unit of **3** can be an electron-

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Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/ejoc.201301719>.

Table 1. Optimization study for the synthesis of **4a**.^[a]



Entry	Base (equiv.)	Solvent	<i>T</i> [°C]	<i>t</i> [h]	4a [%] ^[b]
1	Na ₂ CO ₃ (0.1)	CH ₃ CN	reflux	6	35
2	Na ₂ CO ₃ (0.2)	CH ₃ CN	reflux	6	42
3	Na ₂ CO ₃ (0.5)	CH ₃ CN	reflux	6	55
4	Na ₂ CO ₃ (1)	CH ₃ CN	reflux	2	70
5	Na ₂ CO ₃ (2)	CH ₃ CN	reflux	2	72
6	K ₂ CO ₃ (1)	CH ₃ CN	reflux	2	73
7	CS ₂ CO ₃ (1)	CH ₃ CN	reflux	2	71
8	DBU (1)	CH ₃ CN	reflux	2	52
9	Et ₃ N (1)	CH ₃ CN	reflux	2	44
10	K ₂ CO ₃ (1)	DMF	reflux	2	68
11	K ₂ CO ₃ (1)	THF	reflux	2	60
12	K ₂ CO ₃ (1)	EtOH	reflux	2	61
13	K ₂ CO ₃ (1)	H ₂ O	reflux	2	35
14	K ₂ CO ₃ (1)	CH ₂ Cl ₂	reflux	2	30
15	K ₂ CO ₃ (1)	CH ₃ CN	30	2	35
16	K ₂ CO ₃ (1)	CH ₃ CN	50	2	55

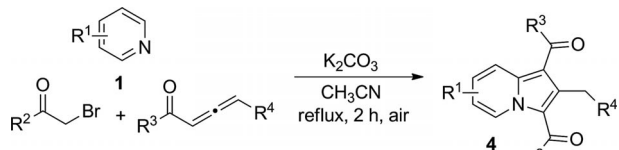
[a] Reaction conditions: **1a** (0.5 mmol), **2a** (0.5 mmol), **3a** (0.5 mmol), solvent (5 mL). [b] Yield of isolated product.

rich (Table 2, Entries 2, 4, 6, 7, and 11) or electron-deficient phenyl (Table 2, Entries 3, 5, 8–10), benzyl (Table 2, Entry 12), or phenethyl groups (Table 2, Entry 13) without showing clear electronic and steric effects. Various functional groups, such as methoxy, cyano, trifluoromethyl, and halides, were well tolerated under the reaction conditions. Promisingly, with allenyl ketones bearing a methyl group on the terminal position of the allene moiety, the reaction still proceeded smoothly to give **4n** and **4o** in good yields (Table 2, entries 14 and 15). Further, substrates bearing an electron-withdrawing group in the R² unit (Table 2, Entries 16–18) gave better yields of the products than those bearing electron-donating groups (Table 2, Entries 19 and 20). Moreover, the reactivity of 4-methylpyridine (**1b**) in this tandem reaction was also studied. Under standard conditions, **1b** reacted smoothly with **2** and **3** to give **4u** and **4v** in good yields (Table 2, Entries 21 and 22). To our delight, not only 2-bromoacetophenones (Table 2, Entries 1–22) but also ethyl 2-bromoacetate participated in this reaction to afford products **4w** and **4x** in an almost equally efficient manner (Table 2, Entries 23 and 24).

In our further study on the scope of substrates, we found that the reaction of **1a** and **2a** with an allenyl ketone bearing a methyl group on the internal position of the allene moiety gave an indolizine bearing only one benzoyl moiety attached to the five-membered heterocyclic ring (i.e., **5a**; Scheme 1).

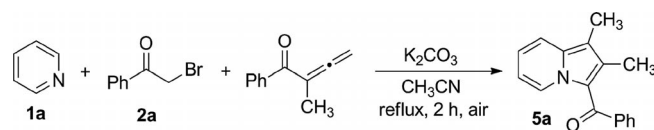
Clearly, this is an interesting finding, as indolizines with different substitution patterns can be obtained. To develop this reaction into a general protocol, pyridines **1**, α -bromo ketones **2**, and α -substituted allenyl ketones **3** were employed as substrates. The results listed in Table 3 show that

Table 2. Scope of the reaction leading to **4**.^[a]



Entry	R ¹	R ²	R ³	R ⁴	4	Yield [%] ^[b]
1	H	C ₆ H ₅	C ₆ H ₅	H	4a	73
2	H	C ₆ H ₅	<i>o</i> -CH ₃ OC ₆ H ₄	H	4b	65
3	H	C ₆ H ₅	<i>o</i> -BrC ₆ H ₄	H	4c	75
4	H	C ₆ H ₅	<i>m</i> -CH ₃ C ₆ H ₄	H	4d	70
5	H	C ₆ H ₅	<i>m</i> -BrC ₆ H ₄	H	4e	78
6	H	C ₆ H ₅	<i>p</i> -CH ₃ OC ₆ H ₄	H	4f	68
7	H	C ₆ H ₅	<i>p</i> -CH ₃ C ₆ H ₄	H	4g	67
8	H	C ₆ H ₅	<i>p</i> -FC ₆ H ₄	H	4h	78
9	H	C ₆ H ₅	<i>p</i> -CF ₃ C ₆ H ₄	H	4i	70
10	H	C ₆ H ₅	<i>p</i> -CNC ₆ H ₄	H	4j	72
11	H	C ₆ H ₅	3,4-(CH ₃ O) ₂ C ₆ H ₃	H	4k	65
12	H	C ₆ H ₅	C ₆ H ₅ CH ₂	H	4l	63
13	H	C ₆ H ₅	C ₆ H ₅ (CH ₂) ₂	H	4m	60
14	H	C ₆ H ₅	<i>p</i> -ClC ₆ H ₄	CH ₃	4n	73
15	H	C ₆ H ₅	C ₆ H ₅	CH ₃	4o	68
16	H	<i>o</i> -BrC ₆ H ₄	<i>p</i> -ClC ₆ H ₄	H	4p	82
17	H	<i>p</i> -FC ₆ H ₄	<i>p</i> -ClC ₆ H ₄	H	4q	80
18	H	<i>p</i> -FC ₆ H ₄	<i>p</i> -BrC ₆ H ₄	H	4r	83
19	H	<i>p</i> -CH ₃ C ₆ H ₄	<i>p</i> -CH ₃ C ₆ H ₄	H	4s	60
20	H	<i>p</i> -CH ₃ C ₆ H ₄	<i>p</i> -ClC ₆ H ₄	H	4t	62
21	<i>p</i> -CH ₃	<i>p</i> -CH ₃ C ₆ H ₄	C ₆ H ₅	H	4u	72
22	<i>p</i> -CH ₃	<i>p</i> -FC ₆ H ₄	C ₆ H ₅	H	4v	78
23	H	OEt	C ₆ H ₅	H	4w	80
24	H	OEt	C ₆ H ₅ (CH ₂) ₂	H	4x	75

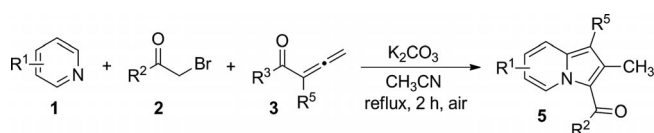
[a] Reaction conditions: **1** (1.0 mmol), **2** (1.0 mmol), **3** (1.0 mmol), K₂CO₃ (1.0 mmol), CH₃CN (10 mL), reflux, 2 h. [b] Yield of isolated product.



Scheme 1. Reactivity of an α -substituted allenyl ketone.

reactions of substrates with either electron-withdrawing or electron-donating groups on the aryl rings of **1** and **2** or substrates with a methyl or ethyl group on the internal position of the allene moiety of **3** proceeded smoothly to give 1,2,3-trisubstituted indolizines **5a–l** with high efficiency (Table 3, Entries 1–12).

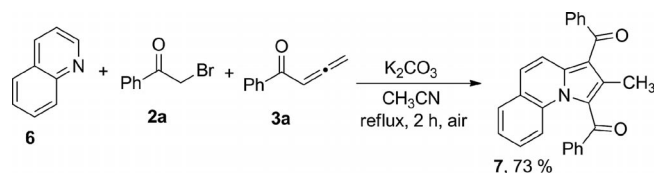
So far, we have successfully developed a simple and efficient synthetic pathway toward 1,2,3-trisubstituted indolizines from the reaction of allenyl ketones with pyridines and α -bromo carbonyl compounds. Bearing in mind that just like indolizines, benzoindolizines such as pyrrolo[1,2-*a*]quinolines and pyrrolo[2,1-*a*]isoquinolines are also of biological and pharmaceutical interest, we then devoted ourselves to investigating the preparation of benzoindolizines according to the strategy developed above by using quinoline and isoquinoline as starting materials. To our delight, treatment of quinoline (**6**) with **2a** and **3a** in

Table 3. Scope of the reaction leading to **5**.^[a]

Entry	R ¹	R ²	R ³	R ⁵	5	Yield [%] ^[b]
1	H	C ₆ H ₅	C ₆ H ₅	CH ₃	5a	78
2	H	<i>p</i> -FC ₆ H ₄	C ₆ H ₅	CH ₃	5b	80
3	<i>m</i> -F	C ₆ H ₅	C ₆ H ₅	CH ₃	5c	70
4	<i>m</i> -F	<i>m</i> -ClC ₆ H ₄	C ₆ H ₅	CH ₃	5d	64
5	<i>p</i> -CH ₃	C ₆ H ₅	C ₆ H ₅	CH ₃	5e	74
6	<i>p</i> -CH ₃	<i>o</i> -ClC ₆ H ₄	C ₆ H ₅	CH ₃	5f	80
7	<i>p</i> -CH ₃	<i>p</i> -CH ₃ OC ₆ H ₄	C ₆ H ₅ CH ₂	CH ₃	5g	72
8	<i>p</i> -CH ₃	<i>m</i> -ClC ₆ H ₄	C ₆ H ₅ CH ₂	CH ₃	5h	82
9	<i>p</i> -CH ₃	<i>p</i> -FC ₆ H ₄	C ₆ H ₅ CH ₂	CH ₃	5i	84
10	H	C ₆ H ₅	C ₆ H ₅	C ₂ H ₅	5j	73
11	<i>p</i> -CH ₃	C ₆ H ₅	C ₆ H ₅	C ₂ H ₅	5k	75
12	<i>p</i> -CH ₃	<i>p</i> -CH ₃ OC ₆ H ₄	C ₆ H ₅ CH ₂	C ₂ H ₅	5l	73

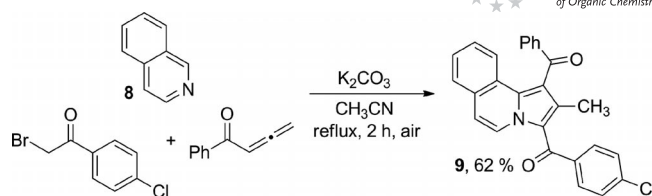
[a] Reaction conditions: **1** (1.0 mmol), **2** (1.0 mmol), **3** (1.0 mmol), K₂CO₃ (1.0 mmol), CH₃CN (10 mL), reflux, 2 h. [b] Yield of isolated product.

the presence of K₂CO₃ (1 equiv.) in refluxing CH₃CN for 2 h afforded the desired (2-methylpyrrolo[1,2-*a*]quinoline-1,3-diyl)bis(phenylmethanone) (**7**) in 78% yield (Scheme 2).

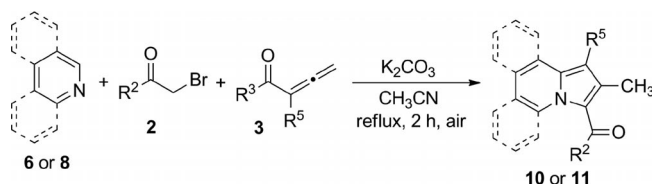
Scheme 2. Preparation of pyrrolo[1,2-*a*]quinoline **7**.

Subsequently, the reactivity of isoquinoline (**8**) was also studied. Promisingly, the reaction of **8** with **2** and **3** under the standard conditions proceeded efficiently to give (1-benzoyl-2-methylpyrrolo[2,1-*a*]isoquinolin-3-yl)(4-chlorophenyl)methanone (**9**) in 62% yield (Scheme 3).

Finally, the reaction of quinoline (**6**) or isoquinoline (**8**) with α -bromo ketones **2** and α -substituted allenyl ketones **3** was also studied. The results listed in Table 4 reveal that both **6** and **8** reacted smoothly with **2** and **3** to give mono-

Scheme 3. Preparation of pyrrolo[2,1-*a*]isoquinoline **9**.

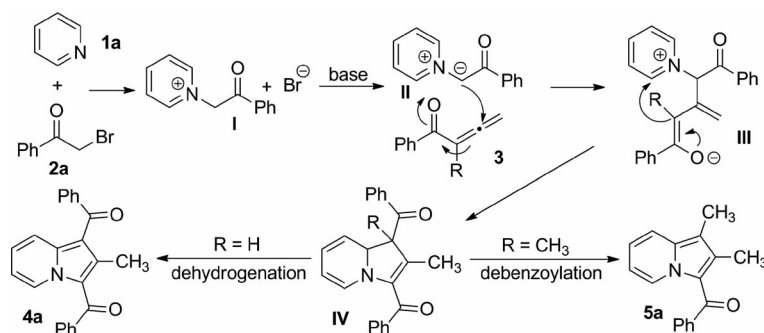
benzoyl-substituted pyrrolo[1,2-*a*]quinolines **10a–c** and pyrrolo[2,1-*a*]isoquinolines **11a–g** with moderate to good efficiency.

Table 4. Scope of the reaction leading to **10** and **11**.^[a]

Entry	6 or 8	R ²	R ³	R ⁵	10 or 11	Yield [%] ^[b]
1	6	C ₆ H ₅	C ₆ H ₅	CH ₃	10a	62
2	6	<i>p</i> -CH ₃ C ₆ H ₄	C ₆ H ₅	CH ₃	10b	60
3	6	C ₆ H ₅	C ₆ H ₅	C ₂ H ₅	10c	68
4	8	<i>o</i> -ClC ₆ H ₄	C ₆ H ₅	CH ₃	11a	90
5	8	<i>p</i> -CH ₃ C ₆ H ₄	C ₆ H ₅	CH ₃	11b	83
6	8	<i>p</i> -FC ₆ H ₄	C ₆ H ₅	CH ₃	11c	92
7	8	<i>p</i> -ClC ₆ H ₄	C ₆ H ₅	CH ₃	11d	88
8	8	C ₆ H ₅	C ₆ H ₅ CH ₂	C ₂ H ₅	11e	85
9	8	<i>p</i> -CH ₃ OC ₆ H ₄	C ₆ H ₅ CH ₂	C ₂ H ₅	11f	83
10	8	<i>p</i> -FC ₆ H ₄	C ₆ H ₅	C ₂ H ₅	11g	93

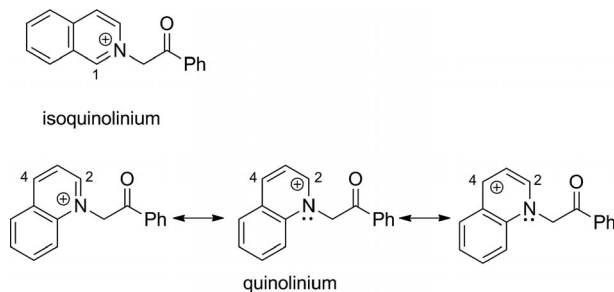
[a] Reaction conditions: **6** or **8** (1.0 mmol), **2** (1.0 mmol), **3** (1.0 mmol), K₂CO₃ (1.0 mmol), CH₃CN (10 mL), reflux, 2 h. [b] Yield of isolated product.

On the basis of the above facts, a tentative mechanistic rationale for the formation of **4a** and **5a** is shown in Scheme 4. First, reaction of **1a** with **2a** forms pyridinium species **I**. Upon treatment with a base, it is deprotonated to give zwitterionic intermediate **II**, which then attacks the central carbon atom of the allene unit of **3** to furnish intermediate **III**. Subsequent intramolecular nucleophilic addition on pyridine affords intermediate **IV**. If R = H, de-

Scheme 4. Plausible pathways for the formation of **4a** and **5a**.

hydrogenation of **IV** occurs to give **4a** as the final product, and in contrast, if $R = \text{Me}$, debenzoylation takes place to give **5a**.

Reactions of **8** are giving higher yields than those of **6**, and on the basis of the above mechanism, this might be explained by the fact that the reaction site in the isoquinolinium species (C-1) is more electrophilic than that in the quinolinium species (C-2), where the positive charge is distributed in between C-2 and C-4 (Scheme 5).^[2] For the isoquinolinium species, the transfer of the positive charge is unfavorable, because it would result in the loss of aromaticity in both cycles.



Scheme 5. Positive charge distribution in the key intermediates.

Conclusions

We have developed an efficient and convenient tandem process for the assembly of 1,2,3-trisubstituted indolizines, pyrrolo[1,2-*a*]quinolines, and pyrrolo[2,1-*a*]isoquinolines through the multicomponent reaction of pyridines (quinoline or isoquinoline) with α -bromo carbonyl compounds and 1,2-allenyl ketones. Notably, allenyl ketones with or without a substituent attached to the internal position of the allene moiety afforded indolizine derivatives with different substitution patterns. With advantages such as readily available starting materials, simple synthetic procedures, good to excellent yields of the products, and mild reaction conditions, the methods developed herein are expected to serve as promising protocols for the construction of relevant nitrogen-containing heterocycles.

Experimental Section

General: The pyridines, quinoline, isoquinoline, and α -bromo ketones were commercial reagents and used without purification. The 1,2-allenyl ketones were prepared by oxidation of the corresponding homopropargyl alcohols, which were prepared by zinc-promoted propargylation of the corresponding aldehydes. ^1H and ^{13}C NMR spectra were recorded at 400 and 100 MHz, respectively. Chemical shifts are reported in ppm from tetramethylsilane as an internal standard. The conversions of the starting materials were monitored by thin-layer chromatography (TLC) by using silica gel plates (silica gel 60 F254, 0.25 mm), and components were visualized by observation under UV light (254 and 365 nm).

Typical Procedure for the Preparation of 4a: K_2CO_3 (1.0 mmol, 138 mg) and 1-phenylbuta-2,3-dien-1-one (**3a**; 144 mg, 1.0 mmol) were added to a flask containing pyridine (**1a**; 79 mg, 1.0 mmol),

2-bromo-1-phenylethanone (**2a**; 199 mg, 1.0 mmol), and CH_3CN (10 mL). The mixture was stirred under reflux. Upon completion of the reaction, as monitored by TLC, the reaction was quenched with aqueous NH_4Cl . Then, the mixture was filtered through Celite, and the filtrate was extracted with ethyl acetate ($3 \times 10 \text{ mL}$). The combined organic phases were dried, filtered, and concentrated under vacuum. The residue was purified by column chromatography on silica gel (20% ethyl acetate/hexane) to give (2-methylindolizine-1,3-diyl)bis(phenylmethanone) (**4a**; 73%).

Supporting Information (see footnote on the first page of this article): Experimental details, characterization data, and ^1H and ^{13}C NMR spectra of all products.

Acknowledgments

We are grateful to the Natural Science Foundation of China (NSFC) (grant numbers 21272058, 21172057), the Research Fund for the Doctoral Program of Higher Education (RFDP) (grant number 20114104110005), and the Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT) (IRT 1061) for financial support.

- [1] a) A. R. Katritzky, C. W. Rees (Eds.), *Comprehensive Heterocyclic Chemistry: The Structure, Reactions, Synthesis and Uses of Heterocyclic Compounds*, Pergamon, Oxford, U.K. **1984**, vols. 1–8; b) W. Flitsch, *Comprehensive Heterocyclic Chemistry II* (Eds.: A. R. Katritzky, C. W. Rees, E. F. V. Scriven), Pergamon, Oxford, U.K. **1996**, vol. 8, p. 237; c) F. J. Swinbourne, J. H. Hunt, G. Klinkert, *Adv. Heterocycl. Chem.* **1979**, 23, 103; d) J. P. Michael, *Nat. Prod. Rep.* **1995**, 12, 535; e) J. P. Michael, *Nat. Prod. Rep.* **2008**, 25, 139.
- [2] A. Hazra, S. Mondal, A. Maity, S. Naskar, P. Saha, R. Paira, K. B. Sahu, P. Paira, S. Ghosh, C. Sinha, A. Samanta, S. Banerjee, N. B. Mondal, *Eur. J. Med. Chem.* **2011**, 46, 2132 and references cited therein.
- [3] Y. Liu, H.-Y. Hu, X.-B. Su, J.-W. Sun, C.-S. Cao, Y.-H. Shi, *Eur. J. Org. Chem.* **2013**, 2020 and references cited therein.
- [4] a) Y. Liu, H.-Y. Hu, Q.-J. Liu, H.-W. Hu, J.-H. Xu, *Tetrahedron* **2007**, 63, 2024; b) X. Fang, Y.-M. Wu, J. Deng, S.-W. Wang, *Tetrahedron* **2004**, 60, 5487.
- [5] a) X. Huang, T. Zhang, *Tetrahedron Lett.* **2009**, 50, 208; b) C. Xie, Y. Zhang, P. Xu, *Synlett* **2008**, 3115.
- [6] a) Y. Shang, M. Zhang, S. Yu, K. Ju, C. Wang, X. He, *Tetrahedron Lett.* **2009**, 50, 6981; b) I. Yavari, Z. Hossaini, M. Sabaghian, *Tetrahedron Lett.* **2006**, 47, 6037; c) A. V. Rotaru, I. D. Druta, T. Oeser, T. J. J. Müller, *Helv. Chim. Acta* **2005**, 88, 1798; d) R. M. Dinica, I. I. Druta, C. Pettinari, *Synlett* **2000**, 1013.
- [7] S. Naskar, M. Banerjee, A. Hazra, S. Mondal, A. Maity, R. Paira, K. B. Sahu, P. Saha, S. Banerjee, N. B. Mondal, *Tetrahedron Lett.* **2011**, 52, 1527.
- [8] a) Z. Mao, X. Li, X. Lin, P. Lu, Y. Wang, *Tetrahedron* **2012**, 68, 85; b) D. Virieux, A.-F. Guillouzie, H.-J. Cristau, *Tetrahedron* **2006**, 62, 3710; c) A. Kapur, K. Kumar, L. Singh, P. Singh, M. Elango, V. Subramanian, V. Gupta, P. Kanwal, M. P. S. Ishar, *Tetrahedron* **2009**, 65, 4593.
- [9] Y. Liu, J.-W. Sun, *J. Org. Chem.* **2012**, 77, 1191.
- [10] Y. Yang, M. Gao, D.-X. Zhang, L.-M. Wu, W.-M. Shu, A.-X. Wu, *Tetrahedron* **2012**, 68, 7338.
- [11] a) B. Yan, Y. Zhou, J. Chen, Y. Liu, *J. Org. Chem.* **2007**, 72, 7783; b) Y. Liu, Z. Song, B. Yan, *Org. Lett.* **2007**, 9, 409.
- [12] a) I. V. Seregin, V. Gevorgyan, *J. Am. Chem. Soc.* **2006**, 128, 12050; b) D. Chernyak, S. B. Gadamssetty, V. Gevorgyan, *Org. Lett.* **2008**, 10, 2307.

- [13] T. Aggarwal, S. Kumar, D. K. Dhaked, R. K. Tiwari, P. V. Bharatam, A. K. Verma, *J. Org. Chem.* **2012**, *77*, 8562.
- [14] a) X. Fan, Y. Wang, Y. Qu, H. Xu, Y. He, X. Zhang, J. Wang, *J. Org. Chem.* **2011**, *76*, 982; b) X. Zhang, X. Jia, L. Fang, N. Liu, J. Wang, X. Fan, *Org. Lett.* **2011**, *13*, 5024; c) H. Xu, X. Zhang, Y. He, S. Guo, X. Fan, *Chem. Commun.* **2012**, *48*, 3121; d) Y. He, X. Zhang, L. Cui, X. Fan, *Chem. Asian J.* **2013**, *8*, 717.
- [15] a) S. Ma, *Acc. Chem. Res.* **2003**, *36*, 701; b) N. Krause, A. S. K. Hashmi, *Modern Allene Chemistry*, Wiley-VCH, Weinheim, **2004**, vol. 2, chapter 10; c) S. Ma, *Chem. Rev.* **2005**, *105*, 2829; d) S. Ma, *Aldrichim. Acta* **2007**, *40*, 91.
- [16] a) B. Alcaide, P. Almendros, T. M. del Campo, *Chem. Eur. J.* **2010**, *16*, 5836; b) C.-Y. Zhou, P. W. H. Chan, C.-M. Che, *Org. Lett.* **2006**, *8*, 325; c) S. Ma, Z. Q. Yu, *Angew. Chem.* **2002**, *114*, 1853; *Angew. Chem. Int. Ed.* **2002**, *41*, 1775; d) D. J. Wallace, R. L. Sidda, R. A. Reamer, *J. Org. Chem.* **2007**, *72*, 1051; e) D. Malhotra, L. P. Liu, G. B. Hammond, *Eur. J. Org. Chem.* **2010**, 6855; f) A. S. Dudnik, A. W. Sromek, M. Rubina, J. T. Kim, A. V. Kel'in, V. Gevorgyan, *J. Am. Chem. Soc.* **2008**, *130*, 1440; g) Y. Xia, A. S. Dudnik, V. Gevorgyan, Y. Li, *J. Am. Chem. Soc.* **2008**, *130*, 6940.

Received: November 15, 2013
Published Online: January 2, 2014