RSC Advances

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/advances

Cite this: DOI: 10.1039/c0xx00000x

www.rsc.org/xxxxxx

ARTICLE TYPE

Efficient Strategy for Construction of 6-Carbamoylfulvene-6-carboxylate Skeletons via [3+2] Cycloaddition of 1-Cyanocyclopropane 1-Ester with β-Nitrostyrenes

Chen Tan, Weijian Ye, Juan Yao, Juanjuan Liu, Shuwen Xue, Yang Li, and Cunde Wang*

Received (in XXX, XXX) Xth XXXXXXXXX 20XX, Accepted Xth XXXXXXXXX 20XX
DOI: 10.1039/b000000x

An efficient and straightforward synthetic protocol has been developed for the preparation of 6-carbamoylfulvene-6-carboxylates via a cycloaddition reaction between 1-cyanocyclopropane 1-esters and β-nitrostyrenes for the generation of a wide range of structurally interesting and pharmacologically significant compounds. The reaction utilises Et_3N promoted C–C bond cleavage, two new C–C bond formations of 1-cyanocyclopropane 1-ester with β-nitrostyrene and simultaneous conversion of cyano group into amide in a domino fashion.

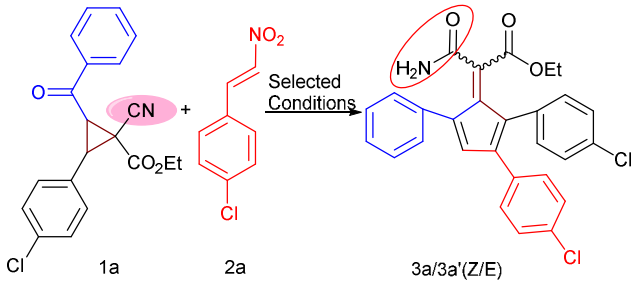
Fulvenes, which exhibit intriguing cross-conjugated molecular structures, are important classes of organic compounds that are not only widely used as specially synthetic building blocks and various kinds of functional materials,[1] but they also has been recognized as privileged scaffolds, which can be found in many natural products and pharmaceuticals.[2] Additionally, due to their abnormal electronic, spectroscopic and chemical properties, fulvenes and their derivatives also have attracted much attention from chemists studying theoretical chemistry.[3] Fulvenes are generally synthesized via the condensation of aldehydes or ketones with cyclopentadiene in the presence of inorganic bases or alkoxides.[4] Recently improved protocol involved secondary amine-promoted this condensation.[5] In addition to the conventional base-promoted fulvene synthesis, coupling reactions of alkynes catalyzed by transition metals was another prominent reaction, such as Pd-catalyzed trimerization of alkynes,[6] Pd catalyzed cross-coupling reactions of alkynes with vinyl halides,[7] and with enone or enal moieties,[8] Ti-catalyzed trimerization of tert-butylacetylene,[9] silver-catalyzed Nazarov-type cyclization of R-hydroxyallenes,[10] gold-catalyzed intramolecular furan/yne cyclization reaction.[11] Additionally, fulvenes were easily accessible through organocatalytic domino reaction of electron-deficient 2,4-dienes with 2-halo-1,3-dicarbonyl compounds or heated cyclization of enediynes in the presence of the stable radical TEMPO (tetramethyl piperidyl oxide),[12] Wolff Rearrangement of ketenes,[13] trifluoromethylation and cyclization of divinyl ketones,[14] or [3+2] annulations of ethyl α-chlorocyclopropaneformates with acetyl acetone.[15] However, these protocols could provide only a limited variety of fulvenes. To address this problem, further development of new and alternative synthetic strategies for functionalized fulvenes is highly desirable.

In recent years, the diverse and often unexpected reactivity of cyclopropanes and their derivatives have drawn considerable attention due to the simplicity of their synthesis and potential for variation of the aryl groups. Cyclopropanes and their derivatives easily undergo a variety of ring-opening reactions under the influence of a variety of conditions. Based on these special reactivity patterns, cyclopropanes and their derivatives have been recognized to be powerful building blocks in organic syntheses.[16] Recently we reported the direct annulation of pyridine derivatives with 1-cyanocyclopropane 1-ester to form indolizine derivatives in a regioselective manner,[17] which stimulated research into new pathways for the construction of cyclic units via the ring-opening reactions of activated donor-acceptor cyclopropanes. Some previous studies revealed the most importantly synthetic value of donor-acceptor cyclopropanes has been extensively demonstrated in the preparation of highly substituted carbocyclic products via formal [3+2] cycloaddition reactions.[18] However, the main research efforts have been devoted to use the skeleton of cyclopropane for the construction of new cyclic skeletons via the ring-opening reactions of activated donor−acceptor cyclopropanes. To the best of our knowledge, no example using [3+2] cycloaddition reactions of 1-cyanocyclopropane 1-ester and β-nitrostyrene as starting materials to construct the five-membered cyclic cores were reported, which two carbons came from the skeleton of cyclopropane and other carbon was from its side chain. In this context, the [3+2] cycloaddition reactions of 1-cyanocyclopropane 1-esters and β-nitrostyrene could provide an easy access to functionalized fulvene frameworks under mildly basic conditions.

Considering their inherent high ring strain, the donor–acceptor (DA) cyclopropanes were easily promoted by basic agents to form a 2-cyano-4-oxobut-2-enoate anion, which could attack an electron-defect double or triple bond as a nuclophilic agent.[19] Our initial experiments focused on the identification of an appropriate basic agent. An inorganic base screening using 1-cyclopropane1-ester **1a** and β-nitrostyrene **2a** as the model substrate and toluene as the solvent at 110 °C was carried out (Table 1). As a result, treatment with weak bases Na_2CO_3, K_2CO_3, Cs_2CO_3 or a strong base NaOH led to no [3+2] cycloaddition reaction (Table 1, entries 1-4). However, while organic base piperidine or triethylamine was used as a promoter, we were pleased to find out

that in the presence of piperidine or triethylamine the formation of the desired product took place (Table 1, entries 5-6). Among them, 0.5 equivalent triethylamine provided the better result, affording two completely separable products as a pair of *syn-anti* isomers, **3a** (upper in TLC) and **3a′** (lower in TLC) in 8% and 15% yields, respectively (entry 6). All these products were well characterized from spectral analysis.

Table 1 Optimization of reaction conditions in the synthesis of **3a**/**3a'**



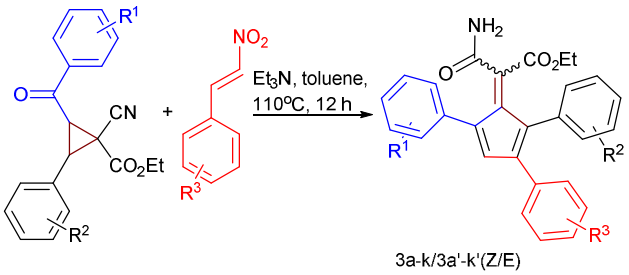
Entry	Base(eq.)	Solvent	T(°C)	t(h)	Yield(%) Z/E(**3a**/**3a'**)
1	Na_2CO_3(1)	PhMe	110	12	0
2	K_2CO_3(1)	PhMe	110	12	0
3	Cs_2CO_3(1)	PhMe	110	12	0
4	NaOH(1)	PhMe	110	12	0
5	Piperidine(1)	PhMe	110	12	trace
6	Et_3N(0.5)	PhMe	110	12	8/15
7	Et_3N(1)	PhMe	110	12	17/24
8	Et_3N(2)	PhMe	110	12	26/34
9	Et_3N(3)	PhMe	110	12	35/41
10	Et_3N(4)	PhMe	110	12	34/40
11	Et_3N(3)	DMF	110	12	0
12	Et_3N(3)	Dioxane	110	12	0
13	Et_3N(3)	$PhNMe_2$	110	12	0
14	Et_3N(3)	PhMe	80	12	19/26
15	Et_3N(3)	PhMe	130	12	30/38
16	Et_3N(3)	PhMe	110	6	trace
17	Et_3N(3)	PhMe	110	18	32/39

[a]isolated yield.

Then our efforts further focused on the amount of Et_3N, the yield was increased slightly when the amount of Et_3N was changed from 0.5 equiv. to 2.0 equiv. (Table 1, entries 6-8). When the amount of Et_3N was increased further to between 3.0 and 4.0 equiv., the reaction was complete after 12 h and the isolated yield was the best, **3a** and **3a′** in ca 35% and 41% yields, respectively (entries 9-10). Moreover, no product was detected when the reaction was performed in DMF, dioxane or $C_6H_5NMe_2$ (entries 11-13). To our great pleasure, 3.0 equiv. Et_3N promoted reaction using toluene as the solvent afforded the products **3a** and **3a′** in excellent 35% and 41% yields in 12 h, respectively (entries 9). When the reaction was performed at 80 °C or 130 °C in 12 h, **3a** and **3a′** were produced in lower yield (entries 14-15). Further reduction or addition in the reaction time also resulted in lower yield of the products.

A series of experiments revealed that the optimal results were obtained when the reaction of ethyl 2-benzoyl-3-(*p*-chlorophenyl)-1-cyanocyclopropane carboxylate (**1a**) and 1-chloro-4-(2-nitrovinyl)benzene (**2a**) together with 3 equiv. Et_3N was carried out in toluene, the resultant mixture was stirred for 12 h at 110 °C, whereby the yields of **3a** and **3a′** reached 35% and 41% (total 76%), respectively (Table 1, entry 9).

Table 2. Synthesis of fulvene derivatives from 1-cyanocyclopropane 1-ester and *β*-nitrostyrene



3a-k/3a'-k'(Z/E)

Entry	R^1	R^2	R^3	Yield (Z/E%)[a]
1	H	*p*-Cl	*p*-Cl	35/41 (**3a**/**3a'**)
2	H	*p*-Cl	*p*-OCH_3	37/42 (**3b**/**3b'**)
3	*p*-CH_3	*p*-Br	*p*-OCH_3	40/48 (**3c**/**3c'**)
4	H	*p*-Br	*p*-OCH_3	39/43 (**3d**/**3d'**)
5	*p*-Cl	*m*-Br	*p*-OCH_3	35/38 (**3e**/**3e'**)
6	*p*-CH_3	*p*-OCH_3	*p*-OCH_3	39/46 (**3f**/**3f'**)
7	*p*-Br	*p*-CH_3	*p*-CH_3	36/42 (**3g**/**3g'**)
8	*p*-Cl	*o*-OCH_3	*p*-OCH_3	33/39 (**3h**/**3h'**)
9	*p*-Br	*m*-Cl	*p*-CH_3	36/41 (**3i**/**3i'**)
10	*p*-OCH_3	*p*-Cl	*o*-OCH_3	37/40 (**3j**/**3j'**)
11	*p*-Cl	*p*-Cl	*p*-OCH_3	78 (**3k**/**3k'**=1/1)[b]

[a]isolated yield.[b]Z/E isomer ratio determined by ^{1}H NMR

To study the scope of this reaction, we explored the use of different 1-cyanocyclopropane 1-esters, and substituted *β*-nitrostyrenes. The results are summarized in Table 2. The reaction tolerates different substituents on the aromatic ring of the 1-cyanocyclopropane 1-esters and substituted *β*-nitrostyrenes, generally, 1-cyanocyclopropane 1-ester with a range of substitutents such as methyl, methoxy, chloro, and bromo at *ortho*-, *meta*- or *para*-positions of phenyl groups all worked well to give 2-carbamoylcyclopentadienylideneacetate derivatives. Substrates with *para*-position phenyl groups gave the products in higher yields than those with *ortho*-, or *meta*-position phenyl groups. The electronic properties of the substituents on the benzene ring of 1-cyanocyclopropane 1-esters had a slight effect on the reaction. The introduction of an electron-withdrawing group such as Cl or Br speeded up the reaction and increased the yield of product, thus facilitating the synthesis of diversely substituted 2-carbamoylcyclopentadienylideneacetates. However, we found that the polarity of the Z-isomer was the almost same as the E-isomer when Cl at *para*-positions of phenyl groups of 1-cyanocyclopropane 1-ester, the resulted Z/E-isomer mixture were not isolated easily by column chromatography (Table 2, entry 11). Additionally, while 1-cyanocyclopropane 1-esters were replaced with 1,1-dicyanopropanes as starting materials, unfortunately the desired 6-carbamoyl-6-cyanofulvenes were not yielded. All corresponding 6-carbamoylfulvene-6-carboxylates were analyzed by their ^{1}H NMR, ^{13}C NMR and MS. Characteristic ^{1}H chemical shift of 6-carbamoylfulvene NH_2 at δ ca 5.40(s) and 5.00(s), respectively, unequivocally indicated the exclusive chemical environment of 6-carbamoyl protons. Although there were slightly differences in ^{1}H NMR and ^{13}C NMR of Z/E-isomer fulvenes, their configurations could not be confirmed by the ^{1}H NMR and ^{13}C NMR spectra of fulvene derivatives. The structure of **3h** was unambiguously solved by X-ray crystallography (Fig. 1).[20] X-ray crystallographic analysis determined that product **3h** possess a carbamoyl and an ester

contiguous substituents at C(6) of fulvene as a Z configuration of an exocyclic double bond. On the basis of spectroscopic evidence the structure of compound **3a-k** was identified as (Z)1,2,4-triaryl-6-carbamoylfulvene-6-carboxylates. Furthermore, the E configuration of another isomer was also confirmed by X-ray crystallography of fulvene **3f′** and **3g′** (Fig. 2).[20]

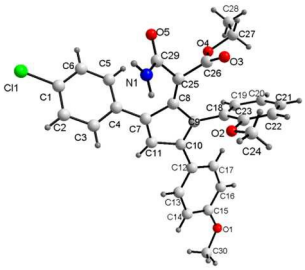


Figure 1. Molecular structure of fulvene **3h**

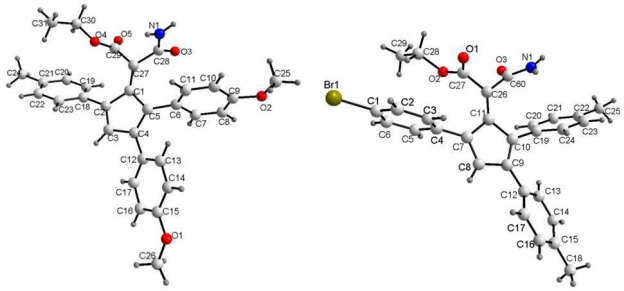
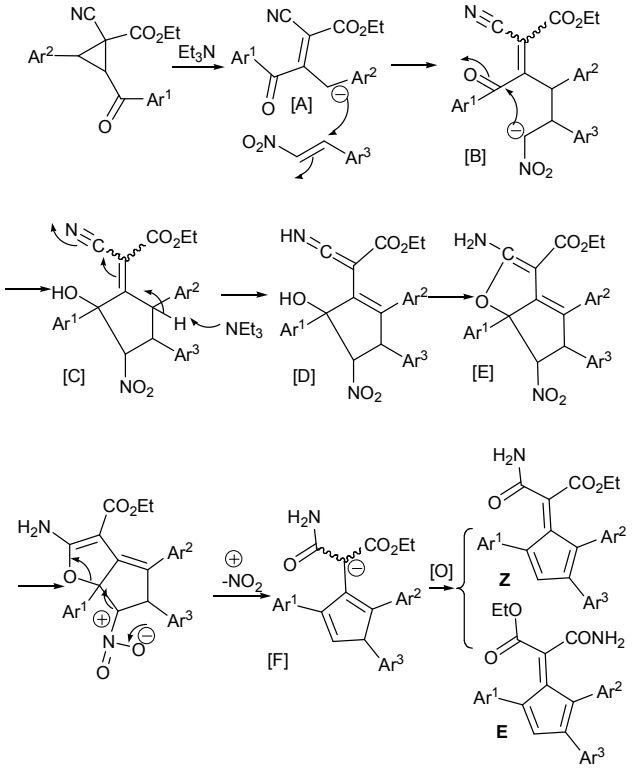


Figure 2. Molecular structure of fulvene **3f′** and **3g′**

A possible mechanism was proposed to rationalize the formation of 6-carbamoylfulvene-6-carboxylates (Scheme 1).



Scheme 1 Possible mechanism in the synthesis of fulvene derivatives.

The key steps involved the generation of a benzyl anion [A] via the carbonyl αH-elimination of 1-cyclopropane1-esters, the nucleophilic addition of [A] with a carbanion to β-nitrostyrene to give an intermediate anion [B], and the subsequent intramolecular nucleophilic addition of anion [B] to carbonyl group forming the cyclopentanol intermediate [C]. Then, in the presence of triethylamine hydrogen 1,5-shift afforded a conjugated enimine intermediate [D]. The cyclopentanol intermediate [D] was transformed to the bicyclic cyclopentane[b]furan intermediate [E] via an intramolecular nucleophilic addition again. Next the cyclopentadiene intermediate [F] was yielded through the denitration of intermediate [E] and furan-ring opening. The 6-carbamoylfulvene-6-carboxylates were finally obtained through the dehydrogenization of the cyclopentadiene intermediate [F] driven by the formation of a conjugated system.

Conclusions

In conclusion, we have developed a straightforward and efficient triethylamine-promoted annulation of 1-cyanocyclopropane 1-esters with *β*-nitrostyrenes for the synthesis of multi-substituted 6-carbamoylfulvene-6-carboxylates as completely separable *syn-anti* isomers, in moderate to good total yields (72−88%) via the reaction of readily available and activated cyclopropanes. This reaction involved the sequential [3+2] cyclization reaction of 2-aroyl-3-aryl-1-cyanocyclopropanecarboxylates with *β*-nitrostyrenes to give the corresponding nitrocyclopentanol, the formation of bicyclic cyclopentane[*b*]furans, removal of nitro group and dehydrogenization. The development of this strategy offered a complementary approach to highly substituted fulvene compounds with advantages that included a variety of cheap and readily available reactants and a wide range of substrates with dense or flexible substitution patterns.

Acknowledgements

Financial support of this research by the National Natural Science Foundation of China (NNSFC 21173181) is gratefully acknowledged by authors. A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

Notes and references

School of Chemistry and Chemical Engineering, Yangzhou University,180 Siwangting Street, Yangzhou 225002, P. R. China. Fax: +86-514-8797-5244; Tel: +86-514-8797-5568; E-mail: wangcd@yzu.edu.cn

† Electronic Supplementary Information (ESI) available: [Reactions conditions and spectra.]. See DOI: 10.1039/b000000x/

1 (a) M. Potowski, J. O. Bauer, C. Strohmann, A. P. Antonchick and H. Waldmann, *Angew. Chem. Int. Ed.* 2012, **51**, 9512; (b) Z. L. He, H. L. Teng and C. J. Wang, *Angew. Chem. Int. Ed.* 2013, **52**, 2934; (c) D. E. Herbert, J. B. Gilroy, A. Staubitz, M. F. Haddow, J. N. Harvey and I. Manners, *J. Am. Chem. Soc.* 2010, **132**, 1988; (d) B. C. Hong, Y. J. Shr, J. L. Wu, A. K. Gupta and K. J. Lin, *Org. Lett.* 2002, **4**, 2249; (e) B. C. Hong, J. L. Wu, A. K. Gupta, M. S. Hallur and J. H. Liao, *Org. Lett.* 2004, **6**, 3453; (f) B. C. Hong, F. L. Chen, S. H. Chen, J. H. Liao and G. H. Lee, *Org. Lett.* 2005, **7**, 557; (g) B. C. Hong, A. K. Gupta, M. F. Wu, J. H. Liao and G. H. Lee, *Org. Lett.* 2003, **5**, 1689; (h) E. Aqad, P. Leriche, G. Mabon, A. Gorgues and V. Khodorkovsky, *Org. Lett.* 2001, **3**, 2329; (i) T. L. Andrew, J. R. Cox and T. M. Swager, *Org. Lett.* 2010, **12**, 5302; (j) K. Kondo, H. Goda, K. Takemoto, H. Aso, T. Sasaki, K. Kawakami, H. Yoshida and J. Yoshida, J. *Mater. Chem.* 1992, **2**, 1097; (k) A. J. Peloquin, R. L. Stone, S. E. Avila, E. R. Rudico, C. B. Horn,

K. A. Gardner, D. W. Ball, J. E. B. Johnson, S. T. Iacono and G. J. Balaich, *J. Org. Chem.* 2012, **77**, 6371; (l) Y. Dong, Y. Geng, J. Ma, R. Huang, *Organometallics* 2006, **25**, 447; (m) A. D. Finke, O. Dumele, M. Zalibera, D. Confortin, P. Cias, G. Jayamurugan, J. P. Gisselbrecht, C. Boudon, W. B. Schweizer, G. Gescheidt and F. Diederich, *J. Am. Chem. Soc.* 2012, **134**, 18139; (n) E. Shurdha, B. K. Repasy, H. A. Miller, K. Dees, S. T. Iacono, D. W. Ball and G. J. Balaich, *RSC Adv.* 2014, **4**, 41989.

2 (a) S. Omura, H. Tomoda and H. Nishida, *J. Antibiot.* 1994, **4**, 148; (b) F. Kuno, K. Otoguro, K. Shiomi, Y. Iwai and S. Omura, *J. Antibiot.* 1996, **49**, 742; (c) V. Nair, C. N. Jayan, K. V. Radhakrishnan, G. Anilkumar and N. P. Rath, *Tetrahedron* 2001, **57**, 5807; (d) K. Strohfeldt and M. Tacke, *Chem. Soc. Rev.* 2008, **37**, 1174; (e) M. Tanasova and S. J. Sturla, *Chem. Rev.* 2012, **112**, 3578; (f) T. D. Lash, D. A. Colby, A. S. Idate and R. N. Davis, *J. Am. Chem. Soc.* 2007, **129**, 13800; (g) B. Devendar, C. P. Wu, C. Y. Chen, H. C. Chen, C. H. Chang, C. K. Ku, C. Y. Tsai and C. Y. Ku, *Tetrahedron* 2013, **69**, 4953; (h) D. Trac, B. Liu, A. C. Pao, S. V. Thomas, M. Park, C. A. Downs, H. P. Ma and M. N. Helms, *Am. J. Physiol. Renal. Physiol.* 2013, **305**, 995; (i) J. L. Arbiser, Fulvene and fulvalene analogs and their use in treating cancers, US 20080275016A1, 2008; (j) D. S. Siegel, G. Piizzi, G. Piersanti and M. Movassaghi, *J. Org. Chem.* 2009, **74**, 9292.

3 (a) R. H. Mitchell, R. Zhang, D. J. Berg, B. Twamley and R. V. Williams, *J. Am. Chem. Soc.* 2009, **131**, 189; (b) I. Garkusha, J. Fulara, A. Nagy and J. P. Maier, *J. Am. Chem. Soc.* 2010, **132**, 14979; (c) C. Dahlstrand, K. Yamazaki, K. Kilsa and H. Ottosson, *J. Org. Chem.* 2010, **75**, 8060.

4 (a) B. C. Hong and J. H. Hong, *Synth. Commun.* 1997, **27**, 3385; (b) G. A. Olah, G. K. Surya Prakash and G. Liang, *J. Org. Chem.* 1977, **42**, 661.

5 N. Coskun and I. Erden, *Tetrahedron*, 2011, **67**, 8607.

6 (a) E. S. Johnson, G. J. Balaich, P. E. Fanwick and I. P. Rothwell, *J. Am. Chem. Soc.* 1997, **119**, 11086; (b) U. Radhakrishnan, V. Gevorgyan and Y. Yamamoto, *Tetrahedron Lett.* 2000, **41**, 1971.

7 (a) G. C. M. Lee, B. Tobias, J. M. Holmes, D. A. Harcourt and M. E. Garst, *J. Am. Chem. Soc.* 1990, **112**, 9330; (b) M. Kotora, H. Matsumura, G. Gao and T. Takahashi, *Org. Lett.* 2001, **3**, 3467; (c) M. Uemura, Y. Takayama and F. Sato, *Org. Lett.* 2004, **6**, 5001.

8 (a) Y. Chen and Y. Liu, *J. Org. Chem.* 2011, **76**, 5274; (b) S. Ye and J. Wu, *Org. Lett.* 2011, **13**, 5980; (c) S. Ye, H. Ren and J. Wu, *J. Comb. Chem.* 2010, **12**, 670; (d) C. S. Bryan and M. Lautens, *Org. Lett*. 2010, **12**, 2754.

9 E. S. Johnson, G. J. Balaich, P. E. Fanwick and I. P. Rothwell, *J. Am. Chem. Soc.* 1997, **119**, 11086.

10 P. Cordier, C. Aubert, M. Malacria, E. Lacote and V. Gandon, *Angew. Chem., Int. Ed.* 2009, **48**, 8757.

11 Y. Chen and Y. Liu, *J. Org. Chem.* 2011, **76**, 5274.

12 (a) J. W. Xie, M. L. Xu, R. Z. Zhang, J. Y. Pan, W. D. Zhu, *Adv. Synth. Catal.* 2014, **356**, 395; (b) B. Konig, W. Pitsch, M. Klein, R. Vasold, M. Prall and P. R. Schreiner, *J. Org. Chem.* 2001, **66**, 1742.

13 R. Koch, R. J. Blanch and C. Wentrup, *J. Org. Chem.* 2014, **79**, 6978.

14 X. Liu, X. Xu, L. Pan, Q. Zhang and Q. Liu, *Org. Biomol. Chem.* 2013, **11**, 6703.

15 Y. Zhu, M. Zhang, H. Yuan and Y. Gong, *Org. Biomol. Chem.* 2014, **12**, 8828.

16 (a) M. A. Cavitt, L. H. Phun and S. France, *Chem. Soc. Rev.* 2014, **43**, 804; (b) T. F. Schneider, J. Kaschel and D. B. Werz, *Angew. Chem., Int. Ed.* 2014, **53**, 5504; (c) H. K. Grover, M. R. Emmett and M. A. Kerr, *Org. Biomol. Chem.*, 2015, **13**, 655; (d) D. J. N. Mack and J. T. Njardarson, *ACS Catal.* 2013, **3**, 272; (e) Z. W. Wang, *Synlett*, 2012, 2311; (f) P. Tang and Y. Qin, *Synthesis* 2012, 2969; (g) S. E. Reisman, R. R. Nani and S. Levin, *Synlett*, 2011, 2437; (h) F. De Simone, T. Saget, F. Benfatti, S. Almeida and J. Waser, *Chem.-Eur. J.* 2011, **17**, 14527; (i) M. Y. Melnikov, E. M. Budynina, O. A. Ivanova and I. V. Trushkov, *Mendeleev Commun.* 2011, **21**, 293; (j) T. P. Lebold and M. A. Kerr, *Pure Appl. Chem.* 2010, **82**, 1797; (k) C. A. Carson and M. A. Kerr, *Chem. Soc. Rev.* 2009, **38**, 3051; (l) F. De Simone and J. Waser, *Chimia*, 2009, **63**, 162; (m) D. Agrawal and V. K. Yadav, *Chem. Commun.* 2008, **44**, 6471; (n) Pellissier, H. *Tetrahedron*, 2008, **64**, 7041; (o) A. Reichelt and S. F. Martin, *Acc. Chem. Res.* 2006, **39**, 433; (p) M. Yu and B. L. Pagenkopf, *Tetrahedron*, 2005, **61**, 321; (r) H. U. Reissig and R. Zimmer, *Chem. Rev.* 2003, **103**, 1151; s) J. Pietruszka, *Chem. Rev.* 2003, **103**, 1051; t) O. G. Kulinkovich, *Chem. Rev.* 2003, **103**, 2597.

17 J. Liu, L. Zhou, W. Ye and C. Wang, *Chem. Commun.* 2014, **50**, 9068.

18 (a) H. Xiong, H. Xu, S. Liao, Z. Xie and Y. Tang, *J. Am. Chem. Soc.* 2013, **135**, 7851; (b) H. Xu, J. P. Qu, S. Liao, H. Xiong and Y. Tang, *Angew. Chem., Int. Ed.* 2013, **52**, 404; (c) Y. Miyake, S. Endo, T. Moriyama and K. Sakata, Y. Nishibayashi, *Angew. Chem., Int. Ed.* 2013, **52**, 1758; (d) W. Zhu, J. Fang, Y. Liu, J. Ren and Z. Wang, *Angew. Chem., Int. Ed.* 2013, **52**, 2032; (e) S. Haubenreisser, P. Hensenne, S. Schroeder and M. Niggemann, *Org. Lett.* 2013, **15**, 2262; (f) Y. A. Volkova, E. M. Budynina, A. E. Kaplun, O. A. Ivanova, A. O. Chagarovskiy, D. A. Skvortsov, V. B. Rybakov, I. V. Trushkov and M. Y. Melnikov, *Chem.–Eur. J.* 2013, **19**, 6586; (g) E. O. Gorbacheva, A. A. Tabolin, R. A. Novikov, Y. A. Khomutova, Y. V. Nelyubina, Y. V. Tomilov and S. L. Ioffe, *Org. Lett.*, 2013, **15**, 350; (h) L. Wu and M. Shi, *Chem.-Eur. J.* 2010, **16**, 1149; (i) T. P. Lebold, A. B. Leduc and M. A. Kerr, *Org. Lett.* 2009, **11**, 3770; (j) C. Perreault, S. R. Goudreau, L. E. Zimmer and A. B. Charette, *Org. Lett.* 2008, **10**, 689; (k) Y. Bai, J. Fang, J. Ren and Z. Wang, *Chem.–Eur. J.* 2009, **15**, 8975; (l) A. Ivanova, E. M. Budynina, Y. K. Grishin, I. V. Trushkov and P. V. Verteletskii, *Angew. Chem., Int. Ed.* 2008, **47**, 1107; (m) M. K. Ghorai, R. Talukdar and D. P. Tiwari, *Chem. Commun.* 2013, **49**, 8205; (n) H. K. Grover, M. R. Emmett and M. A. Kerr, *Org. Biomol. Chem.* 2015, **13**, 655.

19 (a) M. Graziano and S. Chiosi, *J. Chem. Res*. 1989, 44; (b) L. Graziano, R. Iesce, F. Cermola and G. Cimminello, J. Chem. Res. 1992, 4.

20 Crystallographic data for **3h**, **3f′** and **3g′** have been deposited with the Cambridge Crystallographic Data Centre with the deposition number CCDC 1040541, 1037660 and 1023075. These data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax (+44) 1223 336033, e-mail: deposit@ccdc.cam.ac.uk].