Synthesis of novel synthetic intermediates from the reaction of benzimidazole and triazole carbenes with ketenimines and their application in the construction of spiro-pyrroles†

Jun-Ming Mo, Yang-Guang Ma and Ying Cheng*

Received 27th July 2009, Accepted 14th September 2009
First published as an Advance Article on the web 14th October 2009
DOI: 10.1039/b915215f

2-(2-Alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium and 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts were synthesized in good yields from the reaction of benzimidazole and triazole carbenes with ketenimines. Upon treatment with a base, both salts were converted into novel 1,3-dipoles which underwent [3+2] cycloaddition reactions with electron-deficient alkynes and allenes to produce benzimidazole-spiro-pyrroles or triazole-spiro-pyrroles. This work provides novel synthons for the construction of multifunctional spiro-pyrrole derivatives that are not easy accessible by other synthetic methods and are potentially amenable to further transformations.

Introduction

Nucleophilic carbenes, especially *N*-heterocyclic carbenes are versatile intermediates in organic synthesis.[1] Among the reactions of nucleophilic carbenes, those with various heterocumulenes have been continuously explored and have gained important applications. For example, imidazoline carbenes, oxazoline carbenes, acyclic or cyclic dioxycarbene and dithiocarbenes undergo [4+1]-cycloadditions with vinyl isocyanates to afford hydroindolones in good yields,[2] while with aryl isocyanates, the nucleophilic carbenes can either afford 1+1 adducts indole-2-ones[3] or 1+2 adducts imidazoline-2,4-dione derivatives[4] depending on the structures of both reactants. Based on the addition–cyclization reactions of nucleophilic carbenes with isocyanates, Rigby and co-workers have successfully applied the reaction of dimethoxycarbene and bis(alkylthio)carbene with vinyl or indole isocyanates to the total syntheses of alkaloids tazettine, mesembrine and phenserine.[5] Besides isocyanates, nucleophilic carbenes can also undergo cyclization reactions with ketenes. For instance, imidazoline carbenes, dioxycarbenes and dithiocarbenes participate in efficient [4+1]-cycloadditions with vinyl ketenes or bis-ketene producing cyclopentenone or cyclopentenedione derivatives.[6] On the other hand, the cyclization between dimethoxycarbene and diphenylketene followed a different pathway to form a 1+2 adduct, 2,5-bis(diphenylmethylene)-4,4-dimethoxy-1,3-dioxolane.[7] In addition to cycloaddition with heterocumulenes to afford cyclic products, *N*-heterocyclic carbenes are also known to form stable zwitterions in the nucleophilic addition to cumulenes and heterocumulenes, such as allenoates,[8] isothiocyanates,[9] isoselenocyanates,[10] carbon dioxide[11] and carbon disulfide.[12] In recent years, the ambident bis-dipoles derived from the addition of *N*-heterocyclic carbenes to aryl isothiocyanates have been developed into versatile synthons for the construction of novel spiro- and fused thiophene or pyrrole derivatives by our group.[13] Although reactions between nucleophilic carbenes and different heterocumulenes have been well documented, their reaction with ketenimines that are structurally similar to isocyanates and ketenes have been rarely reported. Very recently, we found that thiazole and benzothiazole carbenes underwent cycloaddition with two equivalents of ketenimines to produce thiazole- and benzothiazole-spiro-pyrrole derivatives in good yields.[14] The reaction was proposed to proceed *via* a tandem nucleophilic addition of carbene to the C=N bond of ketenimine followed by [3+2] cycloaddition of the 1,3-dipolar intermediate with the C=C bond of ketenimine. However, the 1,3-dipolar intermediates could not be isolated. We considered that the sulfur atom of thiazoles was not a strong enough electron donor to stabilize the cation centers of dipolar intermediates in these reactions. To find new types of C^+–C–N^- 1,3-dipole that can be used as versatile synthons in the construction of novel pyrrole derivatives, we undertook the current study of the reactions of benzimidazole and triazole carbenes with ketenimines, and explored their synthetic applications.

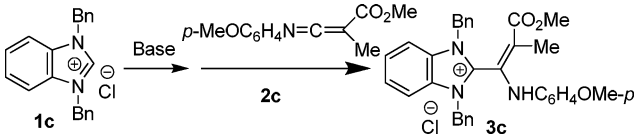
Results and discussion

We started this work with the investigation of the reaction between benzimidazole carbenes and ketenimines. The benzimidazole carbenes were generated in situ from the treatment of benzimidazolium salts **1** with a base. Initially, in dry THF and at room temperature, 1,3-dibenzylbenzimidazolium salt **1c** was treated with NaH for 20 min and then reacted with methyl 3-(*p*-methoxyphenyl)imino-2-methylacrylate **2c** for 3 h. The reaction gave product **3c** in 40% yield. We then optimized the reaction conditions by varying base, reaction temperature and solvent. It was found that the best yield of product **3c** (85%) was obtained using *t*-BuOK as a base in THF at – 20 °C (Table 1, entry 5). Elevation of the reaction temperature in THF led to a slight decrease of the yield of product. Reactions that used NaH, DBU or Hünig's base, or reactions performed in other solvents including dichloromethane,

College of Chemistry, Beijing Normal University, Beijing 100875, China. E-mail: ycheng2@bnu.edu.cn; Fax: +861058805558; Tel: +861058805558

† Electronic supplementary information (ESI) available: Further experimental and characterization details. CCDC reference numbers 740317–740322. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b915215f

Table 1 The reaction of 1,3-dibenzylbenzimidazolium salt **1c** with 3-(*p*-methoxyphenyl)imino-2-methylacrylate **2c** in the presence of a base under different conditions



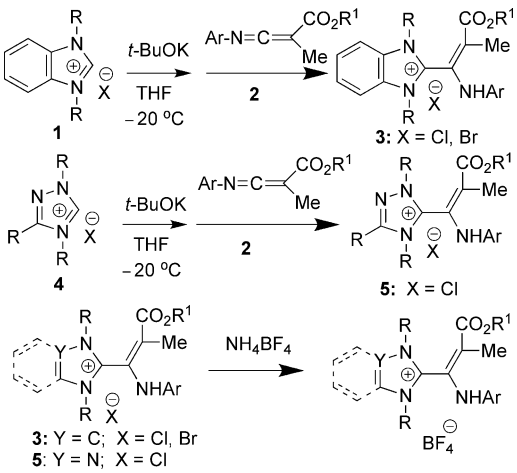
	Reaction conditions[a]				
Entry	base	solvent	temp.	time	Yield of **3c**[b]
1	NaH	THF	rt	3 h	40
2	NaH	THF	–20 °C	5 h	78
3	DBU	THF	–20 °C	12 h	16
4	$(i\text{-Pr})_2$NEt	THF	–20 °C	10 h	-
5	*t*-BuOK	THF	–20 °C	1 h	85
6	*t*-BuOK	THF	rt	0.5 h	79
7	*t*-BuOK	THF	reflux	0.5 h	72
8	*t*-BuOK	CH_2Cl_2	–20 °C	1 h	76
9	*t*-BuOK	CH_3CN	–20 °C	1 h	54
10	*t*-BuOK	Toluene	–20 °C	11 h	8
11	*t*-BuOK	*n*-Hexane	–20 °C	14 h	-

[a] **1c**:**2c**:**base** = 1:1:1; [b] Isolated yields.

acetonitrile, toluene and hexane, afforded product in a lower or very poor yield (Table 1).

To examine the generality of this reaction, both benzimidazole and triazole carbenes bearing alkyl, benzyl or phenyl groups were employed to react with ketenimines substituted by different aryl groups at the nitrogen atom under optimized conditions. As shown in Scheme 1 and Table 2, the reactions of benzimidazolium **1** and triazolium salts **4** with ketenimines **2** in the presence of *t*-BuOK proceeded rapidly and efficiently at –20 °C to afford products **3** and **5**, respectively, in 58–92% yields. Since some chloride or bromide salts of **3** and **5** are not easily purified, these products were then converted into tetrafluoroborate salts by treatment with NH_4BF_4.

The structures of products **3** and **5** were elucidated on the basis of spectroscopic data and microanalysis. The NMR spectra, mass data and elemental analyses indicated that the constitutions of products **3** or **5** were 1+1 adducts of benzimidazolium salts **1** or triazolium salts **4** with ketenimines **2**. According to the spectroscopic data, products **3** and **5** were assigned as 1,3-dialkyl-2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium and 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)-1,3,4-triphenyl-1,2,4-triazolium salts, respectively. X-Ray diffraction analysis of **3g** ascertained the structural assignment, which



Scheme 1 The reaction of benzimidazolium **1** or triazolium salts **4** with ketenimines **2** in the presence of *t*-BuOK.

Table 2 The reactions of benzimidazolium **1** and triazolium salts **4** with ketenimines **2** in the presence of *t*-BuOK under optimized conditions[a]

Entry	**1** or **4**	R, X	**2**	Ar, R^1	**3** or **5**	X	Yield (%)[b]
1	**1a**	Et, Br	**2a**	Ph, Me	**3a**	Br	85
2	**1b**	*n*-Bu, Br	**2a**	Ph, Me	**3b**	BF_4	80
3	**1c**	Bn, Cl	**2c**	*p*-$MeOC_6H_4$, Me	**3c**	Cl	85
4	**1d**	*p*-MeBn, Cl	**2a**	Ph, Me	**3d**	Cl	92
5	**1e**	*p*-ClBn, Cl	**2a**	Ph, Me	**3e**	Cl	74
6	**1e**	*p*-ClBn, Cl	**2b**	*p*-ClC_6H_4, Et	**3f**	Cl	72
7	**1f**	*p*-BrBn, Br	**2a**	Ph, Me	**3g**	BF_4	68
8	**4a**	Ph, Cl	**2a**	Ph, Me	**5a**	Cl	81
9	**4a**	Ph, Cl	**2b**	*p*-ClC_6H_4, Et	**5b**	BF_4	68
10	**4a**	Ph, Cl	**2c**	*p*-$MeOC_6H_4$, Me	**5c**	Cl	70
11	**4a**	Ph, Cl	**2d**	*p*-MeC_6H_4, Me	**5d**	BF_4	74

[a] Reaction conditions: **1** or **4**:**2** = 1:1, *t*-BuOK, THF, –20 °C, 1 h. [b] Isolated yields.

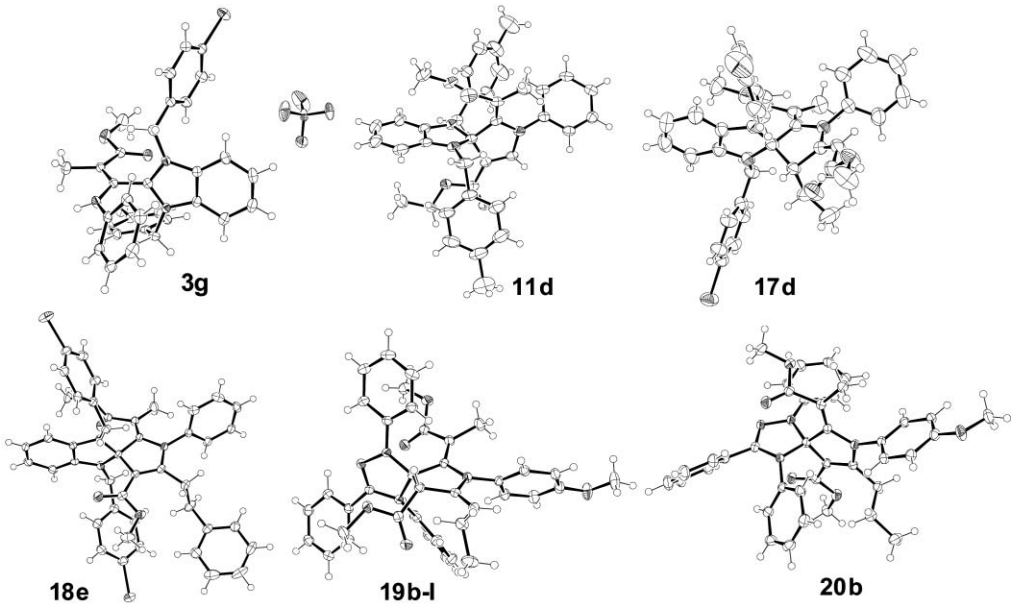
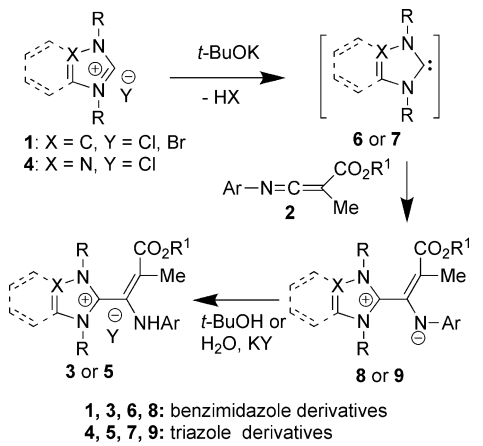


Fig. 1 Ortep drawing of X-ray structures of **4g**, **11d**, **17d**, **18e**, **19b-I**, **20b** (50% probability was chosen for the ellipsoids).

showed the *E*-configured carbon–carbon double bond of **3g** (Fig. 1).[15] Theoretically, products **3** and **5** can have *Z*-configured and *E*-configured stereoisomers, however, no *Z*-configured isomer was observed in these reactions.

Since we have proved that thiazole and benzothiazole carbenes undergo a tandem nucleophilic addition/[3+2] cycloaddition reaction with ketenimines **2** in our previous study,[14] the formation of (2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium **3** or -triazolium salts **5** can be best explained by the nucleophilic addition of benzimidazole carbenes **6** or triazole carbenes **7** to ketenimines **2** to form 1,3-dipolar intermediates **8** or **9**, followed by protonation of dipoles **8** or **9** with butanol or water in solvent and/or in the eluent of column chromatography (Scheme 2). Comparing the current reactions with those between thiazole or benzothiazole carbenes and ketenimines **2**, we found that the dipolar intermediates **8** or **9** derived from benzimidazole or triazole carbenes and ketenimines **2** are more stable than the 1+1 adducts of thiazole or benzothiazole carbenes with ketenimine, since the



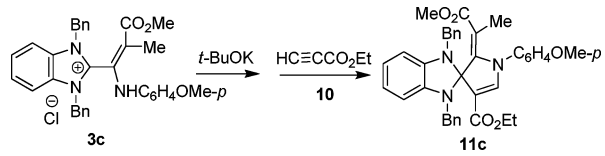
Scheme 2 The proposed mechanism for the reaction of benzimidazolium **1** or triazolium salts **4** with ketenimines **2** in the presence of *t*-BuOK.

former did not further react with ketenimines under reaction conditions while the latter did. This difference is easily understood because the cation centers of intermediates **8** or **9** that are stabilized by the two nitrogen atoms of benzimidazole or triazole are more stable than the cation centers substituted by one nitrogen and one sulfur atom of thiazole or benzothiazole.

With the 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium **3** and 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts **5** in hand, we further explored their applications in organic synthesis. We considered that both benzimidazolium **3** and 1,2,4-triazolium salts **5** can be converted into zwitterions by deprotonation of the arylamino groups of **3** and **5**, and therefore they probably could be used as the precursors of novel 1,3-dipoles. Thus, 1,3-dibenzyl-2-(2-methoxycarbonyl-1-(*p*-methoxyphenyl)amino-1-propenyl)benzimidazolium chloride **3c** was treated with *t*-BuOK and then reacted with ethyl propiolate in THF at room temperature. A red product **11c** was isolated in 41% yield from this reaction. The reaction conditions were then optimized by varying solvents and temperature. As indicated in Table 3, the best yield of **11c** (59%) was obtained from the reaction in toluene at 80 °C. Other solvents including THF, dichloromethane, acetonitrile and hexane led to lower yields and the reaction temperature only slightly affected the yield of product.

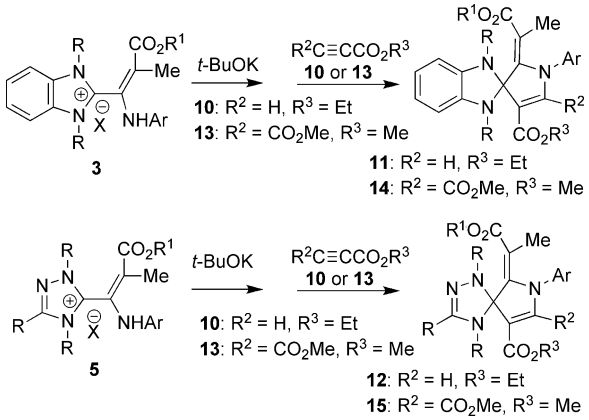
The generality was examined by reacting benzimidazolium **3** and triazolium salts **5** with ethyl propiolate under optimized conditions. Benzimidazolium **3** or triazolium salts **5** were mixed with *t*-BuOK in toluene at room temperature, and then reacted with ethyl propiolate **10** at 80 °C for half an hour to afford benzimidazole-spiro-dihydropyrroles **11** or triazole-spiro-dihydropyrroles **12** in moderate yields (Scheme 3, and Table 4 entries 1–8). The scope of the reaction was further studied by replacement of ethyl propiolate with dimethyl acetylenedicarboxylate (DMAD). Under conditions identical to those used for ethyl propiolate, benzimidazolium **3** and 1,2,4-triazolium salts **5** were deprotonated with *t*-BuOK and reacted with DMAD rapidly to

Table 3 The reaction of 1,3-dibenzyl-2-[2-methoxycarbonyl-1-(*p*-methoxyphenyl)amino-1-propenyl]benzimidazolium chloride **3c** with ethyl propiolate in the presence of *t*-BuOK under different conditions



	Reaction conditions[a]			
Entry	solvent	temp.	time	Yield of **11c**[b]
1	Toluene	rt	3 h	51
2	Toluene	80	0.5 h	59
3	Toluene	reflux	0.5 h	56
4	THF	rt	3 h	41
5	CH_2Cl_2	rt	3 h	29
6	CH_3CN	rt	5 h	29
7	*n*-Hexane	rt	5 h	18

[a] **3c**:**10**:**base** = 1:1:1; [b] Isolated yields.



Scheme 3 The reaction of 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)-benzimidazolium **3** and 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts **5** with ethyl propiolate and dimethyl acetylenedicarboxylate.

afford spiro-dihydropyrroles **14** and **15**, respectively, in 58–71% yields (Scheme 3, and Table 4 entries 9–17).

We next turned our attention to the reactions of benzimidazolium salts **3** and triazolium salts **5** with electron-deficient allenes. Under the optimized conditions for the aforementioned reactions (toluene, 80 °C), the reaction of **3e** with methyl 5-phenylpenta-2,3-dienoate **16b** in the presence of *t*-BuOK formed two products **17b** and **18b** in 50% and 8% yields respectively in 3 h. Spectroscopic data confirmed that compounds **17b** and **18b** were two constitutional isomers. The major product **17b** was derived from cycloaddition of 1,3-dipolar intermediate **8** with the benzyl-substituted C=C bond (electron-rich double bond), while the minor one **18b** was the adduct of the 1,3-dipole and the ester-substituted double bond (electron-deficient double bond). To improve the selectivity for the formation of **17b** and **18b**, the reaction of **3e** with **16b** was examined at different temperatures (Table 5). It was found that, at room temperature and at 60 °C, only product **17b** was isolated in 40% and 62% yields respectively. When the reaction temperature was elevated, the yield of product **18b** increased. To our delight, we observed the transformation of product **17b** to **18b** in refluxing toluene. Finally, 53% yield of **18b** was isolated from the reaction in refluxing toluene for 48 h. Thus, the two isomers **17b** and **18b** can be obtained respectively as major product under different conditions.

The reactions of different benzimidazolium salts **3** with allenes **16** were then carried out under the optimized conditions for selective formation of products **17** or **18**. In toluene and at 60 °C, benzimidazolium salts **3** were treated with *t*-BuOK and reacted with allenes **16** for 3 h to produce benzimidazole-spiro-tetrahydropyrroles **17** in 48–62%, while the same reaction afforded 46–53% yields of benzimidazole-spiro-dihydropyrroles **18** along with 14–15% yields of **17** after heating in refluxing toluene for 48 h (Scheme 4, equ. 1; Table 6, entries 1–7).

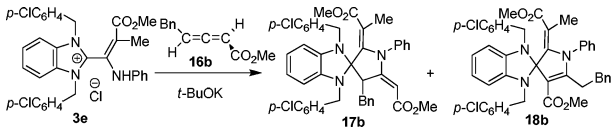
Followed the reaction of benzimidazolium salts **3** with allenes, triazolium salts **5** were also employed to react with allenes **16**. In toluene and at 60 °C, triazolium salts **5** reacted with allenes **16** in the presence of *t*-BuOK to afford two triazole-spiro-tetrahydropyrroles **19-I** and **19-II** in 26–49% and 14–24%

Table 4 The reaction of **3** or **5** with ethyl propiolate **10** and with dimethyl acetylenedicarboxylate (DMAD) **13** in the presence of *t*-BuOK under optimized conditions[a]

Entry	Starting materials	R	R^1	Ar	Product	Yield (%)[b]
1	**3c** + **10**	Bn	Me	*p*-$MeOC_6H_4$	**11c**	59
2	**3d** + **10**	*p*-MeBn	Me	Ph	**11d**	61
3	**3e** + **10**	*p*-ClBn	Me	Ph	**11e**	58
4	**3f** + **10**	*p*-ClBn	Et	*p*-ClC_6H_4	**11f**	47
5	**3g** + **10**	*p*-BrBn	Me	Ph	**11g**	54
6	**5b** + **10**	Ph	Et	*p*-ClC_6H_4	**12b**	55
7	**5c** + **10**	Ph	Me	*p*-$MeOC_6H_4$	**12c**	68
8	**5d** + **10**	Ph	Me	*p*-MeC_6H_4	**12d**	57
9	**3b** +**13**	*n*-Bu	Me	Ph	**14b**	70
10	**3d** +**13**	*p*-MeBn	Me	Ph	**14d**	69
11	**3e** +**13**	*p*-ClBn	Me	Ph	**14e**	58
12	**3g** + **13**	*p*-BrBn	Me	Ph	**14g**	58
13	**5a** + **13**	Ph	Me	Ph	**15a**	71
14	**5b** +**13**	Ph	Et	*p*-ClC_6H_4	**15b**	58
15	**5c** + **13**	Ph	Me	*p*-$MeOC_6H_4$	**15c**	61
16	**5d** + **13**	Ph	Me	*p*-MeC_6H_4	**15d**	64

[a] Toluene, 80 °C, 0.5 h; [b] Isolated yields.

Table 5 The reaction of 1,3-di(*p*-chlorobenzyl)-2-(2-methoxycarbonyl-1-phenylamino-1-propenyl)benzimidazolium chloride **3e** with methyl 5-phenylpenta-2,3-dienoate **16b** in the presence of *t*-BuOK in toluene



	Reaction conditions[a]			Yield (%)[b]	
Entry	solvent	temp.	time	**17b**	**18b**
1	Toluene	rt	5 h	40	–
2	Toluene	60 °C	3 h	62	–
3	Toluene	80 °C	3 h	50	8
4	Toluene	reflux	3 h	48	16
5	Toluene	reflux	12 h	36	29
6	Toluene	reflux	24 h	33	35
7	Toluene	reflux	36 h	20	47
8	Toluene	reflux	48 h	14	53

[a] **3c**:**16b**:**base** = 1:1:1; [b] Isolated yields.

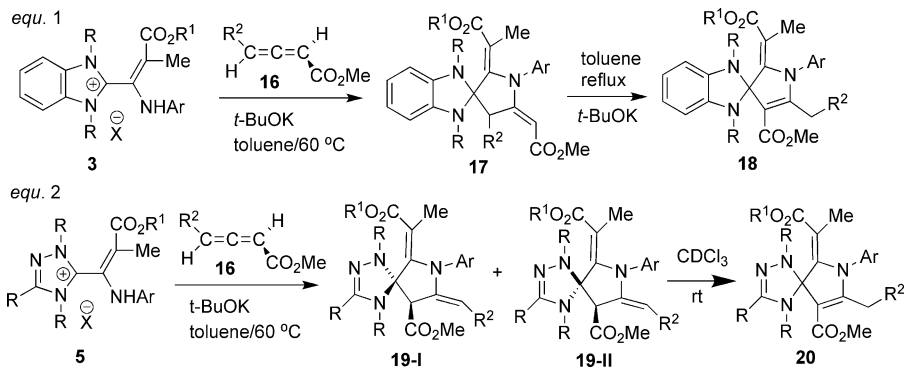
yields, respectively (Scheme 4, equ. 2; Table 6, entries 8–10.). Products **19-I** and **19-II** were confirmed to be diastereoisomers by their spectroscopic data, and both of them were obtained from the cycloaddition of dipolar intermediates **9** with the ester-substituted double bond of allenes **16**. Isomers **19-I** and **19-II** could not transform into each other by varying the reaction conditions. However, triazole-spiro-tetrahydropyrroles **19-I** were observed to convert slowly into triazole-spiro-dihydropyrroles **20** during the recrystallization process. The quantitative transformation of triazole-spiro-tetrahydropyrroles **19** to triazole-spiro-dihydropyrroles **20** was achieved by keeping **19** in deuterium chloroform for a few days (Scheme 4, equ. 2; Table 6, entries 11–12).

The structures of the products were elucidated on the basis of spectroscopic data and microanalysis. The NMR spectra, mass data and elemental analyses indicated products **11**, **12**, **14**, **15**, **17**, **18**, **19**, or **20** being derived from 1+1 addition of (2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium **3** or -triazolium salts **5** with alkynes **10**, **13** or allenes **16**, with the loss of a molecule of HCl, HBr or HBF_4. The exact structures of **11d**,

Table 6 The reaction of **3** or **5** with allenes **16** in the presence of *t*-BuOK

	Starting materials								
Entry		R	R^1	Ar		R^2	Reaction conditions	Yield of product (%)[a]	
1	**3e**	*p*-ClBn	Me	Ph	**16a**	Et	Toluene, 60 °C, 5 h	**17a**	58
2	**3e**	*p*-ClBn	Me	Ph	**16b**	Bn	Toluene, 60 °C, 3 h	**17b**	62
3	**3e**	*p*-ClBn	Me	Ph	**16b**	Bn	Toluene, reflux, 48 h	**17b**	14
								18b	53
4	**3f**	*p*-ClBn	Et	*p*-ClC_6H_4	**16b**	Bn	Toluene, 60 °C, 5 h	**17c**	53
5	**3g**	*p*-BrBn	Me	Ph	**16a**	Et	Toluene, 60 °C, 5 h	**17d**	48
6	**3g**	*p*-BrBn	Me	Ph	**16b**	Bn	Toluene, 60 °C, 3 h	**17e**	51
7	**3g**	*p*-BrBn	Me	Ph	**16b**	Bn	Toluene, reflux, 48 h	**17e**	15
								18e	46
8	**5a**	Ph	Me	Ph	**16a**	Et	Toluene, 60 °C, 3 h	**19a-I**	49
								19a-II	14
9	**5c**	Ph	Me	*p*-$MeOC_6H_4$	**16a**	Et	Toluene, 60 °C, 3 h	**19b-I**	26
								19b-II	24
10	**5d**	Ph	Me	*p*-MeC_6H_4	**16a**	Et	Toluene, 60 °C, 3 h	**19c-I**	38
								19c-II	21
11	**19a-I** **19a-II**	Ph	Me	Ph		Et	$CDCl_3$, rt, 1–3 days	**20a**	quantitative conversion[b]
12	**19b-I** **19b-II**	Ph	Me	*p*-$MeOC_6H_4$		Et	$CDCl_3$, rt, 1–3 days	**20b**	quantitative conversion[b]

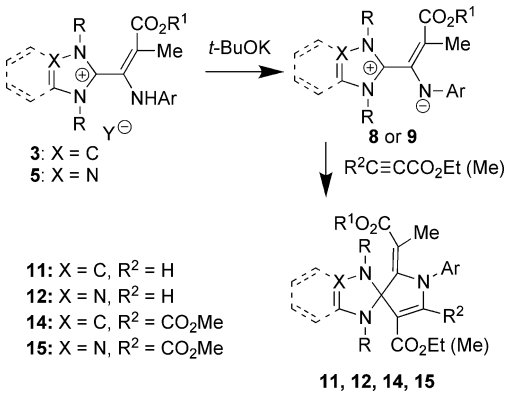
[a] Isolated yields. [b] Detected by TLC and ^1H NMR.



Scheme 4 The reaction of 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium **3** or 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts **5** with allenes **16** in the presence of *t*-BuOK.

17d, **18e**, **19b-I** and **20b** were unambiguously established by single crystal X-ray diffraction analysis (Fig. 1).[15] It is worth noting that in the reactions of benzimidazolium **3** and triazolium salts **5** with allenes **16**, only *E,E*-configured products **17** and **19** were detected. The predominant formation of *E*-configured exocyclic C=C bonds of products **17** and **19** was most probably due to the fact that the *E*-configured double bonds could avoid the huge steric repulsion between the *N*-aryl group on the pyrrole ring and the carbonyl or alkyl groups on the exocyclic C=C bonds.

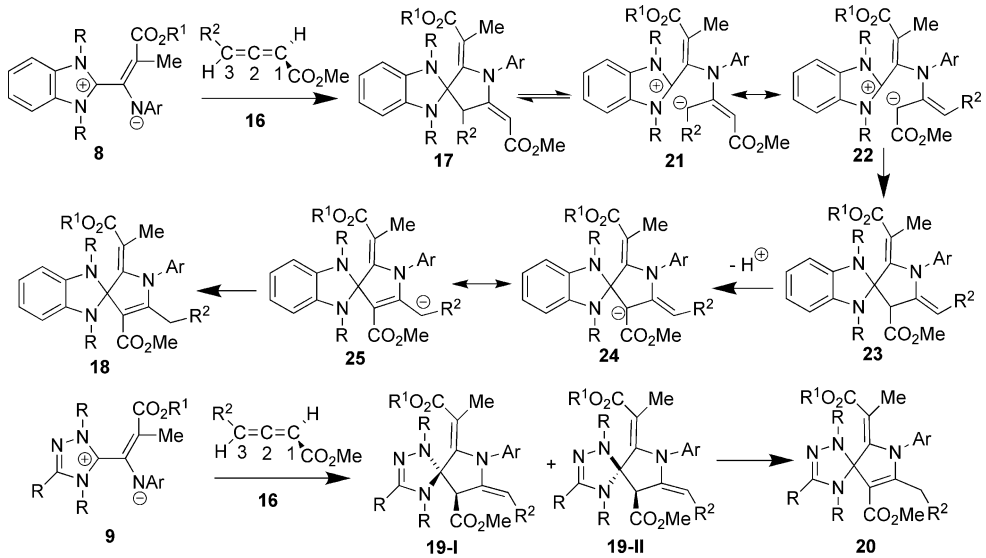
The formation of benzimidazole-spiro-pyrroles **11**, **14**, **17**, **18** or triazole-spiro-pyrroles **12**, **15**, **19**, **20** can be best explained by [3+2] cycloaddition of the dipolar intermediates **8** or **9** with alkynes or allenes. Deprotonation of 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium **3** or 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts **5** with *t*-BuOK formed 1,3-dipolar intermediates **8** or **9**, respectively. Cycloaddition of dipoles **8** or **9** with ethyl propiolate or DMAD produced benzimidazole-spiro-dihydropyrroles **11**, **14** or triazole-spiro-dihydropyrroles **12**, **15**, respectively (Scheme 5).



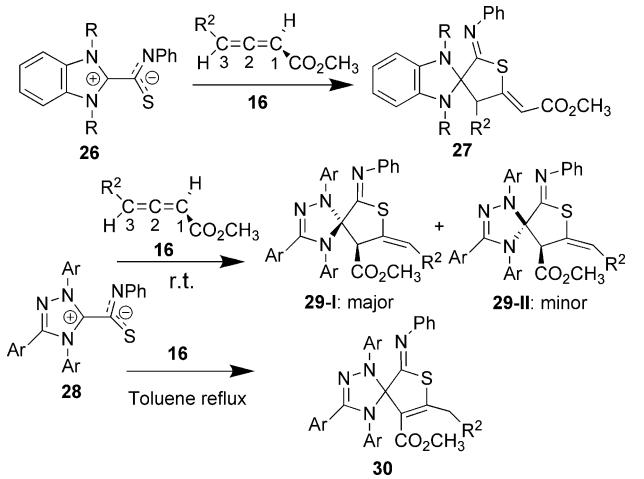
Scheme 5 The proposed mechanism for the formation of products **11**, **12**, **14**, **15**.

Since allenes **16** have two different carbon–carbon double bonds, an electron-deficient C(1)–C(2) double bond (carbonyl substituted C=C bond) and an electron-rich C(2)–C(3) double bond (alkyl substituted C=C bond), the cycloaddition of dipolar intermediates **8** and **9** with allenes **16** was regioselective. In the reaction of benzimidazole carbene-derived dipoles **8** with allenes **16**, dipoles **8** selectively attacked the electron-rich C(2)–C(3) double bond of allenes to form benzimidazole-spiro-tetrahydropyrroles **17** at a lower temperature. At a higher temperature, spiro-tetrahydropyrroles **17** isomerized into their constitutional isomers **23**, probably *via* zwitterionic intermediates that can be represented as two resonant structures **21** and **22**. Under the reaction conditions, intermediates **23** rearranged into thermodynamically more stable conjugated products **18** by shifting the exocyclic C=C bond of **23** to the endocyclic double bond. Since a concerted suprafacial 1,3-H shift is a symmetry forbidden process, the isomerization of intermediates **23** to product **18** was most probably through an allyl anion intermediate **24**, by deprotonation of the acidic proton adjacent both to carbonyl and vinyl groups in the presence of *t*-BuOK. Contrary to benzimidazole carbene-derived dipoles **8**, triazole carbene-derived dipoles **9** selectively cyclized with the electron-deficient C(1)–C(2) double bond of allenes **16** to form a pair of diastereomers **19-I** and **19-II**. In solvent, the spontaneous isomerization of triazole-spiro-tetrahydropyrroles **19** to triazole-spiro-dihydropyrroles **20** should followed the same pathway as that from intermediates **23** to products **18**, since triazole derivatives **19** are organic bases that probably self-catalyze the rearrangement of double bond (Scheme 6).

The different selectivity of benzimidazole and triazole carbene-derived dipoles **8** and **9** toward two double bonds of allenes **16** was in good agreement with our recent discovery on the regioselectivity of [3+2] cycloaddition reaction of allenes **16** with 2-thiocarbamoyl benzimidazolium **26** and with 2-thiocarbamoyl triazolium inner salts **28**, which were ambident 1,3-dipoles derived respectively from 1+1 addition of benzimidazole and triazole carbenes with aryl isothiocyanates. We have demonstrated experimentally that 2-thiocarbamoyl benzimidazolium inner salts **26** predominately undergo cycloaddition reaction with the electron-rich C(2)–C(3) double bond of allenes **16**, while 2-thiocarbamoyl triazolium inner salts **28** prefer to cyclize with the electron-deficient



Scheme 6 The proposed mechanisms for the formation of products **17**, **18**, **19**, **20**.



Scheme 7 The reaction of 2-thiocarbamoyl benzimidazolium **26** and 2-thiocarbamoyl triazolium inner salts **28** with allenes **16**.[16]

C(1)–C(2) double bond of allenes **16** (Scheme 7).[16] Generally, the ester carbonyl-substituted C(1)–C(2) double bond is more active than the alkyl-substituted C(2)–C(3) double bond toward nucleophiles due to the electronic preference. However, our theoretical study[16] indicated that both the cycloaddition of benzimidazolium inner salts **26** with the C(2)=C(3) bond of allene **16** and triazolium inner salts **28** with the C(1)=C(2) bond of **16** are kinetically more favorable than the other pathways. The unusual regioselectivity of the reaction between benzimidazole dipole **26** and allene **16** is most probably due to the repulsion between the phenyl ring of benzimidazolium **26** and the ester carbonyl group of **16** in the transition state of reaction between **26** and C(1)=C(2) bond of **16**. That means the steric effect counterbalances the electronic effect in this reaction. Comparing the current study illustrated in Scheme 6 with the previous work in Scheme 7, we found that although the unstable dipolar intermediates **8** and the stable dipoles **26**, or **9** and **28**, are structurally different, the regioselectivity of their [3+2] cycloaddition reaction with allenes **16** keeps quite the same. That is the benzimidazole-carbene derived 1,3-dipoles prefer to react with the C(2)=C(3) bond of **16**, but triazole-carbene derived 1,3-dipoles prefer to react with the C(1)=C(2) bond of **16**. This work further demonstrated that it is the structure of the heterocyclic carbene that controls the regioselectivity of cycloaddition between carbene-derived dipoles and allenes.

Conclusions

In summary, we have prepared 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium salts **3** and 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts **5** in good to excellent yields from the reaction of benzimidazole and triazole carbenes with 3-arylimino-2-methylacrylates (*C*-alkoxycarbonyl-*N*-arylketenimines). Benzimidazolium salts **3** and triazolium salts **5** were converted into novel 1,3-dipolar intermediates, namely 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium inner salts and 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium inner salts, by treatment with *t*-BuOK. These resulting dipolar intermediates underwent [3+2] cycloaddition reactions with electron-deficient alkynes and allenes to produce benzimidazole-spiro-pyrroles or triazole-spiro-pyrroles generally in moderate yields. This work has provided novel and versatile synthons for the construction of multifunctional spiro-pyrrole derivatives, which are not easy accessible by other synthetic methods and are potentially amenable to further transformations.

Experimental

Melting points are uncorrected. ^{1}H NMR (500 or 400 MHz) and ^{13}C NMR (125 or 100 MHz) were recorded in the indicated solvents. J values are reported in Hz. IR spectra were recorded using an AVATAR 360 FT-IR spectrometer. Mass spectra were recorded on a Trace MS (EI) or Surveyor MSQ Plus (ESI) instrument and elemental analyses were performed on a GMBH Vario EL instrument. Column chromatography was performed using 200–300 mesh silica gel or neutral Al_2O_3. For full characterization for all isolated products see the ESI.†

1. The preparation of 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium salts 3 or 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts 5 from the reaction of benzimidazole or triazole carbenes with ketenimines

Under a nitrogen atmosphere and at –20 °C, benzimidazolium chloride or bromide salts **1** (0.5 mmol) or triazolium chloride salts **4** (0.5 mmol) were mixed with *t*-BuOK (0.5 mmol) in dry THF (30 mL) and stirred for 5 min. Ketenimines **2** (0.5 mmol) were added to the reaction mixture and the mixture was stirred at –20 °C for 1 h. After removal of solvent under vacuum at room temperature, the residue was chromatographed on a neutral Al_2O_3 column eluting with a mixture of acetone and methanol (5:1). The eluent was evaporated and the 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium chlorides or bromides **3** or 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium chlorides **5** were isolated in 68–93% or 68–81% yields, respectively. The benzimidazolium or triazolium chlorides or bromides **3** or **5** were converted into tetrafluoroborate salts by treatment with NH_4BF_4 in methanol.

(*E*)-1,3-Diethyl-2-(2-methoxycarbonyl-1-phenylamino-1-propenyl)benzimidazolium bromide (3a). 85%, yellow crystals (ethyl acetate and petroleum ether), mp 179–181 °C; ν_{max}/cm^{-1} 3342, 2729, 1688, 1590, 1546, 1514; δ_H (500 MHz, $CDCl_3$) 10.34 (brs, 1H), 7.69–7.73 (m, 2H), 7.61 (dd, J = 6.0, 2.8 Hz, 2H), 7.31 (t, J = 8.1 Hz, 2H), 7.13 (d, J = 7.9 Hz, 2H), 7.03 (t, J = 7.4 Hz, 1H), 4.40–4.51 (m, 4H), 3.63 (s, 3H), 1.96 (s, 3H), 1.54 (t, J = 7.3 Hz, 6H); δ_C (125 MHz, $CDCl_3$) 168.1, 147.3, 139.9, 131.4, 131.1, 129.0, 126.9, 123.0, 119.3, 113.3, 113.0, 52.1, 42.3, 16.4, 13.9; MS (ESI): 364 (M^+). Anal. Calcd for $C_{22}H_{26}BrN_3O_2$: C 59.46, H 5.90, N 9.46; Found: C 59.55, H 6.04, N 9.60.

(*E*)-5-(2-Methoxycarbonyl-1-phenylamino-1-propenyl)-1,3,4-triphenyl-1,2,4-triazolium chloride (5a). 81%, yellow crystals (ethyl acetate and petroleum ether), mp 171–173 °C; ν_{max}/cm^{-1} 2698, 1676, 1589, 1541, 1496, 1451; δ_H (400 MHz, $CDCl_3$) 11.96 (s, 1H), 7.98 (dd, J = 8.0, 2.0 Hz, 2H), 7.70–8.10 (br, 1H), 7.60 (d, J = 7.4 Hz, 2H), 7.30–7.51 (m, 10H), 7.02 (t, J = 7.7 Hz, 2H), 6.82 (t, J = 7.3 Hz, 1H), 6.44 (d, J = 7.8 Hz, 2H), 3.63 (s, 3H), 1.33 (s, 3H); δ_C (100 MHz, $CDCl_3$) 168.7, 153.5, 150.8, 139.7, 135.1, 131.9, 131.8, 131.24, 131.18, 130.6, 129.8, 129.52, 129.45, 128.8, 128.2, 127.8, 125.8, 123.0, 122.5, 119.2, 112.5, 52.1, 15.6; MS (EI):

194 (100), 296 (60), 486 (M^+-1, 6%), 487 (M^+, 3%). Anal. Calcd for $C_{31}H_{27}ClN_4O_2$: C 71.19, H 5.20, N 10.71; Found: C 70.92, H 5.09, N 10.42.

2. General procedure for the reaction of 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium salts 3 or 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts 5 with ethyl propiolate or DMAD

Under a nitrogen atmosphere and at room temperature, benzimidazolium salts **3** (0.5 mmol) or triazolium salts **5** (0.5 mmol) were mixed with *t*-BuOK (0.6 mmol) in dry toluene. After the temperature was elevated to 80 °C, ethyl propiolate or DMAD (0.6 mmol) was added to the mixture. The reaction mixture was stirred at 80 °C for half an hour and then the solvent was removed under vacuum. The products **11**, **12**, **14** or **15** were isolated by chromatography on a silica gel column eluting with a mixture of petroleum ether (60–90 °C) and ethyl acetate (5:1).

(*E*)-Ethyl 1,3-dibenzyl-2′-(1-methoxycarbonylethylidene)-1′-(*p*-methoxyphenyl)-1,1′,2′,3-tetrahydrospiro[benzimidazole-2,3′-pyrrole]-4′-carboxylate (11c). 53%, orange crystals (ethyl acetate and petroleum ether), mp 172–173 °C; ν_{max}/cm^{-1} 1713, 1687, 1612, 1598, 1506; δ_H (400 MHz, $CDCl_3$) 7.38 (d, J = 6.7 Hz, 4H), 7.27–7.29 (m, 6H), 7.09 (s, 1H), 6.82 (d, J = 8.8 Hz, 2H), 6.79 (d, J = 8.8 Hz, 2H), 6.49 (dd, J = 5.2, 3.2 Hz, 2H), 6.15 (dd, J = 5.4, 3.2 Hz, 2H), 4.36 (d, J = 16.0 Hz, 2H), 4.30 (d, J = 16.0 Hz, 2H), 3.89 (q, J = 7.1 Hz, 2H), 3.79 (s, 3H), 3.09 (s, 3H), 1.59 (s, 3H), 0.88 (t, J = 7.1 Hz, 3H); δ_C (100 MHz, $CDCl_3$) 170.2, 163.6, 157.8, 148.3, 147.7, 140.4, 138.6, 134.2, 128.3, 128.1, 126.9, 124.9, 117.7, 114.5, 114.0, 108.2, 103.3, 96.0, 59.3, 55.5, 52.0, 49.2, 17.7, 13.7; MS (EI): 90 (100), 395 (60), 615 (M^+, 20%). Anal. Calcd for $C_{38}H_{37}N_3O_5$: C 74.13, H 6.06, N 6.82; Found: C 73.80, H 6.22, N 6.73.

(*E*)-Ethyl 1′-(*p*-chlorophenyl)-2′-(1-ethoxycarbonylethylidene)-1,3,4-triphenyl-1,1′,2′,4-tetrahydrospiro[1,2,4-triazole-2,3′-pyrrole]-4′-carboxylate (12b). 56%, red crystals (ethyl acetate and petroleum ether), mp 134–136 °C; ν_{max}/cm^{-1} 1716, 1613, 1593, 1493; δ_H (400 MHz, $CDCl_3$) 7.47 (dd, J = 7.7, 1.3 Hz, 2H), 7.44 (s, 1H), 7.15–7.29 (m, 12H), 7.07 (d, J = 8.0 Hz, 2H), 6.80 (t, J = 7.1 Hz, 1H), 6.60 (d, J = 8.7 Hz, 2H), 4.11–4.15 (m, 1H), 3.95–4.06 (m, 3H), 1.52 (s, 3H), 1.05 (t, J = 7.1 Hz, 3H), 1.01 (t, J = 7.1 Hz, 3H); δ_C (100 MHz, $CDCl_3$) 168.4, 163.1, 148.2, 146.1, 143.8, 143.3, 139.4, 138.8, 131.3, 129.4, 128.8, 128.7, 128.6, 128.5, 128.3, 128.1, 128.0, 126.7, 123.8, 119.1, 118.1, 114.3, 111.1, 94.2, 61.5, 59.7, 17.7, 14.2, 13.9; MS (EI): 180 (100), 632 (M^+, 15%). Anal. Calcd for $C_{37}H_{33}ClN_4O_4$: C 70.19, H 5.25, N 8.85; Found: C 70.39, H 5.59, N 8.41.

(*E*)-Dimethyl 1,3-dibutyl-2′-(1-methoxycarbonylethylidene)-1′-phenyl-1,1′,2′,3-tetrahydrospiro[benzimidazole-2,3′-pyrrole]-4′,5′-dicarboxylate (14b). 70%, red crystals (ethyl acetate and petroleum ether), mp 128–129 °C; ν_{max}/cm^{-1} 1747, 1716, 1690, 1610, 1515, 1492; δ_H (400 MHz, $CDCl_3$) 7.41 (t, J = 7.7 Hz, 2H), 7.33 (t, J = 7.0 Hz, 1H), 7.28 (d, J = 7.7 Hz, 2H), 6.49 (brs, 2H), 6.14 (dd, J = 5.0, 3.2 Hz, 2H), 3.68 (s, 3H), 3.46 (s, 3H), 3.14 (brs, 4H), 2.98 (s, 3H), 1.49–1.66 (m, 4H), 1.42 (s, 3H), 1.31–1.39 (m, 4H), 0.94 (t, J = 7.4 Hz, 6H); δ_C (100 MHz, $CDCl_3$) 170.1, 163.3, 162.3, 148.6, 147.3, 139.6, 139.4, 129.6, 127.9, 126.4, 117.0, 115.3, 104.9, 101.6, 94.9, 52.9, 52.0, 51.0, 44.2, 30.1, 20.6, 17.0, 13.9; MS (EI): 44 (100), 313 (40), 502 (45), 561 (M^+, 10%). Anal. Calcd for $C_{32}H_{39}N_3O_6$: C 68.43, H 7.00, N 7.48; Found: C 68.66, H 6.93, N 7.47.

(*E*)-Dimethyl 2′-(1-methoxycarbonylethylidene)-1,1′3,4-tetraphenyl-1,1′,2′,4-tetrahydrospiro[1,2,4-triazole-2,3′-pyrrole]-4′,5′-dicarboxylate (15a). 71%, red crystals (ethyl acetate and petroleum ether), mp 159–160 °C; ν_{max}/cm^{-1} 1748, 1713, 1620, 1593, 1493; δ_H (400 MHz, $CDCl_3$) 7.48 (dd, J = 6.4, 1.7 Hz, 2H), 7.34 (dd, J = 6.4, 1.8 Hz, 2H), 7.21–7.29 (m, 11H), 7.13 (d, J = 7.7 Hz, 2H), 6.85 (t, J = 7.2 Hz, 1H), 6.61–6.63 (m, 2H), 3.70 (s, 3H), 3.64 (s, 3H), 3.55 (s, 3H), 1.35 (s, 3H); δ_C (100 MHz, $CDCl_3$) 169.0, 162.8, 161.7, 150.5, 146.2, 143.9, 143.0, 138.7, 138.3, 129.3, 129.0, 128.9, 128.5, 128.3, 128.12, 128.07, 127.9, 126.9, 126.1, 119.4, 117.6, 114.1, 106.2, 93.7, 53.1, 52.7, 51.3, 16.5; MS (EI): 180 (100), 628 (M^+, 15%). Anal. Calcd for $C_{37}H_{32}N_4O_6$: C 70.69, H 5.13, N 8.91; Found: C 70.56, H 4.85, N 8.76.

3. General procedure for the reaction of 2-(2-alkoxycarbonyl-1-arylamino-1-propenyl)benzimidazolium salts 3 or 5-(2-alkoxycarbonyl-1-arylamino-1-propenyl)triazolium salts 5 with allenes 16

Method A. Under a nitrogen atmosphere, benzimidazolium salts **3** (0.5 mmol) or triazolium salts **5** (0.5 mmol) were mixed with *t*-BuOK (0.6 mmol) in dry toluene at room temperature. When the temperature was elevated to 60 °C, allene **16** (0.5 mmol) was added to the reaction mixture, and the mixture was stirred for 3–5 h at 60 °C. After removal of solvent under vacuum, the products **17**, or **19-I** and **19-II** were isolated, respectively, by chromatography on a silica gel column eluting with a mixture of petroleum ether (60–90 °C) and ethyl acetate (7:1). **19-I** and **19-II** can be converted into **20** by standing in deuterium chloroform for a few days.

Method B. Under a nitrogen atmosphere and at room temperature, benzimidazolium salts **3** (0.5 mmol) were mixed with *t*-BuOK (0.6 mmol) in dry toluene. After allene **16** (0.5 mmol) was added, the reaction mixture was stirred for 48 h in refluxing toluene. The solvent was removed under vacuum, and the compounds **18** and **17** were isolated as major and minor products by chromatography on a silica gel column eluting with a mixture of petroleum ether (60–90 °C) and ethyl acetate (7:1).

(*E*,*E*)-Methyl 2-(1,3-di(*p*-chlorobenzyl)-4′-ethyl-5′-methoxycarbonylmethylidene-1′-phenyl-1,3-dihydrospiro[benzimidazole-2,3′-pyrrolidine]-2′-ylidene)propanoate (17a). 58% from method A, yellow crystals (ethyl acetate and petroleum ether), mp 197–199 °C; ν_{max}/cm^{-1} 1701, 1640, 1601, 1503, 1490; δ_H (400 MHz, $CDCl_3$) 7.43 (t, J = 8.0 Hz, 2H), 7.24–7.36 (m, 9H), 7.06 (d, J = 7.6 Hz, 2H), 6.58 (dt, J = 7.6, 1.0 Hz, 1H), 6.49 (dt, J = 7.6, 1.0 Hz, 1H), 6.09 (d, J = 7.3 Hz, 1H), 5.88 (d, J = 7.3 Hz, 1H), 4.76 (s, 1H), 4.63 (d, J = 17.9 Hz, 1H), 4.56 (d, J = 17.2 Hz, 1H), 4.51 (d, J = 17.2 Hz, 1H), 4.26 (d, J = 17.9 Hz, 1H), 4.21–4.23 (m, 1H), 3.49 (s, 3H), 2.86 (s, 3H), 1.97–2.05 (m, 1H), 1.52–1.58 (m, 1H), 1.41 (s, 3H), 0.83 (t, J = 7.4 Hz, 3H); δ_C (100 MHz, $CDCl_3$) 170.5, 167.1, 162.2, 146.2, 139.9, 139.8, 138.7, 138.0, 136.8, 132.6, 132.3, 129.9, 128.6, 128.5, 128.1, 127.9, 127.1, 119.0, 117.8, 106.9, 104.9, 103.0, 96.4, 91.3, 56.7, 52.1, 50.6, 50.4, 49.7, 22.1, 17.1, 10.8; MS (EI): 125 (100), 681 (M^+, 2%). Anal. Calcd for $C_{39}H_{37}Cl_2N_3O_4$: C 68.62, H 5.46, N 6.16; Found: C 68.67, H 5.45, N 5.97.

(*E*)-Methyl 1,3-di(*p*-bromobenzyl)-2′-(1-methoxycarbonylethylidene)-5′-phenethyl-1′-phenyl-1,1′,2′,3-tetrahydrospiro[benzimidazole-2,3′-pyrrole]-4′-carboxylate (18e). 46% from method B, yellow crystals (ethyl acetate and petroleum ether), mp 134–135 °C; ν_{max}/cm^{-1} 1710, 1692, 1617, 1592, 1500; δ_H (400 MHz, $CDCl_3$) 7.38–7.41 (m, 7H), 7.29 (d, J = 8.4 Hz, 4H), 7.12–7.17 (m, 3H), 6.77–6.81 (m, 4H), 6.52 (brs, 2H), 6.16 (brs, 2H), 4.27 (brs, 4H), 3.46 (s, 3H), 3.04 (s, 3H), 2.57–2.62 (m, 2H), 2.30–2.34 (m, 2H), 1.16 (s, 3H); δ_C (100 MHz, $CDCl_3$) 170.7, 164.5, 160.5, 146.7, 140.4, 140.2, 138.7, 137.7, 131.1, 130.3, 129.5, 128.9, 128.6, 128.4, 128.1, 126.2, 120.8, 117.8, 112.0, 103.1, 101.6, 94.8, 52.0, 50.5, 48.6, 33.8, 28.6, 16.6; MS (ESI): 831 (M^+, 45%), 833 (100), 835 (55). Anal. Calcd for $C_{44}H_{39}Br_2N_3O_4$: C 63.40, H 4.72, N 5.04; Found: C 63.13, H 4.95, N 4.84.

(2′*E*,5′*E*,3′*S*,4′*R*) or (2′*E*,5′*E*,3′*R*,4′*S*)-Methyl 2′-(1-methoxycarbonylethylidene)-1,1′,3,4-tetraphenyl-5′-propylidene-1,4-dihydrospiro[1,2,4-triazole-2,3′-pyrrolidine]-4′-carboxylate (19a–I). 49%, yellow crystals (ethyl acetate and petroleum ether), mp 164-166 °C; ν_{max}/cm^{-1} 1744, 1715, 1653, 1594, 1493; δ_H (400 MHz, CD_3COCD_3, 40 °C) 7.72 (t, J = 3.7 Hz, 2H), 7.47 (d, J = 6.3 Hz, 2H), 7.24-7.33 (m, 13H), 6.85-6.88 (m, 1H), 6.59 (br, 2H), 4.92 (s, 1H), 4.70 (dt, J = 7.6, 2.4 Hz, 1H), 3.52 (s, 3H), 3.51 (s, 3H), 1.97-2.01 (m, 1H), 1.81-1.88 (m, 1H), 1.07 (s, 3H), 0.94 (t, J = 7.3 Hz, 3H); δ_C (100 MHz, CD_3COCD_3) 170.2, 169.5, 148.5, 143.2, 143.0, 140.5, 139.9, 137.8, 130.5, 130.4, 129.95, 129.8, 129.5, 129.49, 129.46, 129.0, 128.7, 128.1, 127.2, 120.6, 116.5, 105.0, 103.4, 94.7, 52.5, 51.8, 50.0, 22.5, 16.2, 14.8; MS (ESI): 613 (M+1). Anal. Calcd for $C_{38}H_{36}N_4O_4$: C 74.49, H 5.92, N 9.14; Found: C 74.46, H 5.49, N 9.09.

(2′*E*,5′*E*,3′*R*,4′*R*) or (2′*E*,5′*E*,3′*S*,4′*S*)-Methyl 2′-(1-methoxycarbonylethylidene)-1,1′,3,4-tetraphenyl-5′-propylidene-1,4-dihydrospiro[1,2,4-triazole-2,3′-pyrrolidine]-4′-carboxylate (19a–II). 14%, yellow crystals (ethyl acetate and petroleum ether), mp 147–149 °C; ν_{max}/cm^{-1} 1753, 1719, 1594; δ_H (400 MHz, CD_3COCD_3) 7.41 (t, J = 7.8 Hz, 4H), 7.27–7.36 (m, 11H), 7.17 (t, J = 7.2 Hz, 2H), 7.01 (br, 2H), 6.82 (t, J = 7.2 Hz, 1H), 4.54 (dt, J = 7.6, 2.4 Hz, 1H), 4.39 (s, 1H), 3.48 (s, 3H), 3.35 (s, 3H), 1.82–1.88 (m, 1H), 1.76–1.80 (m, 1H), 1.22 (s, 3H), 0.83 (t, J = 7.3 Hz, 3H); δ_C (100 MHz, $CDCl_3$) 174.8, 173.1, 152.9, 150.9, 148.2, 145.3, 143.6, 143.3, 134.5, 134.4, 134.3, 134.1, 133.9, 133.8, 133.2, 133.0, 132.9, 132.6, 132.5, 124.7, 121.7, 108.9, 107.5, 99.3, 60.7, 56.8, 56.4, 26.6, 21.1, 18.9; MS (ESI): 613 (M+1). Anal. Calcd for $C_{38}H_{36}N_4O_4$: C 74.49, H 5.92, N 9.14; Found: C 74.29, H 5.74, N 9.04.

(*E*)-Methyl 2′-(1-methoxycarbonylethylidene)-1,1′,3,4-tetraphenyl-5′-propyl-1,1′,2′,4-tetrahydrospiro[1,2,4-triazole-2,3′-pyrrole]-4′-carboxylate (20a). orange crystals (ethyl acetate and petroleum ether), mp 166–168 °C; ν_{max}/cm^{-1} 1717, 1689, 1609, 1592, 1493; δ_H (400 MHz, CD_3COCD_3) 7.47–7.49 (m, 5H), 7.28–7.33 (m, 8H), 7.09–7.18 (m, 6H), 6.73 (t, J = 7.0 Hz, 1H), 3.49 (s, 3H), 3.47 (s, 3H), 2.48–2.55 (m, 1H), 2.34–2.41 (m, 1H), 1.26 (s, 3H), 1.12–1.24 (m, 2H), 0.63 (t, J = 7.3 Hz, 3H); δ_C (100 MHz, CD_3COCD_3) 170.3, 164.5, 164.0, 147.0, 146.0, 144.5, 139.8, 139.7, 130.4, 130.3, 130.2, 129.7, 129.6, 129.5, 129.4, 129.0, 128.9, 128.8, 127.6, 119.4, 114.9, 113.9, 102.0, 94.6, 52.6, 50.5, 28.4, 21.9, 16.3, 14.4; MS (ESI): 613 (M+1). Anal. Calcd for $C_{38}H_{36}N_4O_4$: C 74.49, H 5.92, N 9.14; Found: C 74.39, H 6.04, N 9.15.

Acknowledgements

This work was supported by the National Natural Science Foundation of China for Distinguished Young Scholars (No. 20525207), the National Natural Science Foundation of China (No. 20832006 and 20672013), the Ministry of Science and Technology of China (2009ZX09501-006) and Beijing Municipal Commission of Education.

Notes and references

1 Y. Cheng and O. Meth-Cohn, *Chem. Rev.*, 2004, **104**, 2507–2530; J. Warkentin, *Adv. Carbene Chem.*, 1998, **2**, 245–295.
2 J. H. Rigby and Z. Wang, *Org. Lett.*, 2002, **4**, 4289–4291; J. H. Rigby, A. Cavezza and G. Ahmed, *J. Am. Chem. Soc.*, 1996, **118**, 12848–12849; J. H. Rigby, A. Cavezza and M. J. Heeg, *Tetrahedron Lett.*, 1999, **40**, 2473–2476; J. H. Rigby and S. Laurent, *J. Org. Chem.*, 1999, **64**, 1766–1767; J. H. Rigby, S. Laurent, W. Dong and M. D. Danca, *Tetrahedron*, 2000, **56**, 10101–10111.
3 J. H. Rigby and P. J. Burke, *Heterocycles*, 2006, **67**, 643–653.
4 D. Enders, K. Breuer, J. Runsink and J. H. Teles, *Liebigs Ann.*, 1996, 2019–2028; A. R. Katritzky, D. Cheng, P. Leeming, I. Ghiviriga, C. M. Hartshorn and P. J. Steel, *J. Heterocycl. Chem.*, 1996, **33**, 1935–1941; R. W. Hoffmann, B. Hagenbruch and D. M. Smith, *Chem. Ber.*, 1977, **110**, 23–36; M. Reiffen and R. W. Hoffmann, *Chem. Ber.*, 1977, **110**, 37–48; P. Couture, J. K. Terlouw and J. Warkentin, *J. Am. Chem. Soc.*, 1996, **118**, 4214–4215; P. Couture and J. Warkentin, *Can. J. Chem.*, 1997, **75**, 1281–1294; E. Haug, W. Kantlehner, H. Hagen, P. Speh and H.-J. Braeuner, *Liebigs Ann. Chem.*, 1988, **1988**, 605–607; R. W. Hoffmann and M. Reiffen, *Chem. Ber.*, 1977, **110**, 49–52; M. El-Saidi, K. Kassam, D. L. Pole, T. Tadey and J. Warkentin, *J. Am. Chem. Soc.*, 1992, **114**, 8751–8752.
5 J. H. Rigby, A. Cavezza and M. J. Heeg, *J. Am. Chem. Soc.*, 1998, **120**, 3664–3670; J. H. Rigby and W. Dong, *Org. Lett.*, 2000, **2**, 1673–1675; J. H. Rigby and S. Sidique, *Org. Lett.*, 2007, **9**, 1219–1221.
6 J. H. Rigby and Z. Wang, *Org. Lett.*, 2003, **5**, 263–264; J. D. Colomvakos, I. Egle, J. Ma, D. L. Pole, T. T. Tidwell and J. Warkentin, *J. Org. Chem.*, 1996, **61**, 9522–9527.
7 R. W. Hoffmann, W. Lilienblum and B. Dittrich, *Chem. Ber.*, 1974, **107**, 3395–3407.
8 R. Gompper and U. Wolf, *Liebigs Ann. Chem.*, 1979, **1979**, 1406–1425.
9 B. Cetinkaya, E. Cetinkaya, J. A. Chamizo, P. B. Hitchcock, H. A. Jasim, H. Kücükbay and M. F. Lappert, *J. Chem. Soc., Perkin Trans. 1*, 1998, 2047–2054; H. E. Winberg and D. D. Coffman, *J. Am. Chem. Soc.*, 1965, **87**, 2776–1777; M. Regitz, J. Hocker, W. Schöessler, B. Weber and A. Liedhegener, *Justus Liebigs Ann. Chem.*, 1971, **748**, 1–19; H. J. Schoenherr and H. W. Wanzlick, *Chem. Ber*, 1970, **103**, 1037–1046; A. Takamizawa, K. Hirai and S. Matsumoto, *Tetrahedron Lett.*, 1968, **9**, 4027–4030; A. Takamizawa, S. Matsumoto and S. Sakai, *Chem. Pharm. Bull.*, 1974, **22**, 293–298.
10 J.-H. Zhang and Y. Cheng, *Org. Biomol. Chem.*, 2009, **7**, 3264.
11 N. Kuhn, M. Steimann and G. Weyers, *Z. Naturforsch., Teil B*, 1999, **54**, 427–433.
12 N. Kuhn, E. Niquet, M. Steimann and I. Walker, *Z. Naturforsch, B: Chem. Sci.*, 1999, **54**, 1181–1187; N. Kuhn, H. Bohnen and G. Henkel, *Z. Naturforsch, B: Chem. Sci.*, 1994, **49**, 1473–1480; S. Dummling, B. Speiser, N. Kuhn and G. Weyers, *Acta Chem. Scand.*, 1999, **53**, 876–886; N. Kuhn, G. Weyers, S. Dummling and B. Speiser, *Phosphorus, Sulfur Silicon Relat. Elem.*, 1997, **128**, 45–62; W. Krasuski, D. Nikolaus and M. Regitz, *Liebigs Ann. Chem.*, 1982, **1982**, 1451–1465.
13 M.-F. Liu, B. Wang and Y. Cheng, *Chem. Commun.*, 2006, 1215–1217; Y.-G. Ma and Y. Cheng, *Chem. Commun.*, 2007, 5087–5089; Y. Cheng, M.-F. Liu, D.-C. Fang and X.-M. Lei, *Chem.–Eur. J.*, 2007, **13**, 4282–4292; J.-Q. Li, R.-Z. Liao, W.-J. Ding and Y. Cheng, *J. Org. Chem.*, 2007, **72**, 6266–6269; Y. Cheng, Z.-M. Kang, Y.-G. Ma, J.-H. Peng and M.-F. Liu, *Tetrahedron*, 2008, **64**, 7362–7368; B. Wang, J.-Q. Li and Y. Cheng, *Tetrahedron Lett.*, 2008, **49**, 485–489.
14 Y. Cheng, Y.-G. Ma, X.-R. Wang and J.-M. Mo, *J. Org. Chem.*, 2009, **74**, 850–855.
15 Crystal data for **3g**: $C_{32}H_{28}BBr_2F_4N_3O_2$, M = 733.20, T = 113 K, monoclinic, space group P21/n, a = 10.8497(12), b = 17.4399(18),

c = 16.2784(17) Å, α = 90°, β = 98.769(3)°, γ = 90°, V = 3044.2(6) Å^3, Z = 4, ρ_{calcd} = 1.600 g cm^{-3}, absorption coefficient 2.723 mm^{-1}, reflections collected/unique 29525/7233 [R(int) = 0.0535], final R indices [I>2sigma(I)], R_1 = 0.0442, wR_2 = 0.1051. Crystal data for **11d**: $C_{39}H_{39}N_3O_4$, M = 613.73, T = 113 K, triclinic, space group P-1, a = 9.9376(10), b = 13.3618(14), c = 14.3300(16) Å, α = 68.670(8)°, β = 73. 901(9)°, γ = 72.586(8)°, V = 1660.6(3) Å^3, Z = 2, ρ_{calcd} = 1.227 g cm^{-3}, absorption coefficient 0.080 mm^{-1}, reflections collected/unique 17084/5832 [R(int) = 0.0473], final R indices [I>2sigma(I)], R_1 = 0.0764, wR_2 = 0.2439. Crystal data for **17d**: $C_{39}H_{37}Br_2N_3O_4$, M = 771.54, T = 296 K, monoclinic, space group P21/c, a = 9.3172(1), b = 21.0352(2), c = 17.9002(2) Å, α = 90°, β = 96.187(1)°, γ = 90°, V = 3487.81(6) Å^3, Z = 4, ρ_{calcd} = 1.469 g cm^{-3}, absorption coefficient 2.369 mm^{-1}, reflections collected/unique 21027/7987 [R(int) = 0.0198], final R indices [I>2sigma(I)], R_1 = 0.0440, wR_2 = 0.1235. Crystal data for **18e**: $C_{44}H_{39}Br_2N_3O_4$, M = 833.60, T = 113 K, monoclinic, space group P21/n, a = 7.7608(16), b = 18.522(4), c = 26.266(5) Å, α = 90°, β = 94.70°, γ = 90°, V = 3762.8(13) Å^3, Z = 4, ρ_{calcd} = 1.471 g cm^{-3}, absorption coefficient 2.203 mm^{-1}, reflections collected/unique 38112/6631 [R(int) = 0.0542], final R indices [I>2sigma(I)], R_1 = 0.0379, wR_2 = 0.0981. Crystal data for **19b-I**: $C_{39}H_{38}N_4O_5$, M = 642.73, T = 113 K, monoclinic, space group P 21/n, a = 11.8253(19), b = 18.626(3), c = 15.232(2) Å, α = 90°, β = 92.810(3)°, γ = 90°, V = 3350.8(9) Å^3, Z = 4, ρ_{calcd} = 1.274 g cm^{-3}, absorption coefficient 0.085 mm^{-1}, reflections collected/unique 33818/7984 [R(int) = 0.0413], final R indices [I>2sigma(I)], R_1 = 0.0494, wR_2 = 0.1289. Crystal data for **20b**: $C_{39}H_{38}N_4O_5$, M = 642.73, T = 113 K, monoclinic, space group P 21/c, a = 9.2415(9), b = 20.801(2), c = 17.0490(16) Å, α = 90°, β = 92.631°, γ = 90°, V = 3273.9(5) Å^3, Z = 4, ρ_{calcd} = 1.304 g cm^{-3}, absorption coefficient 0.087 mm^{-1}, reflections collected/unique 405442/7773 [R(int) = 0.0512], final R indices [I>2sigma(I)], R_1 = 0.0466, wR_2 = 0.1180. CCDC 740317 (compound **3g**), 740318 (compound **11d**), 740319 (compound **17d**), 740320 (compound **18e**), 740321 (compound **19b-I**) and 740322 (compound **20b**) contain the supplementary crystallographic data for this paper.† These data can be obtained free of charge from the Cambridge Crystallographic Data centre *via* www.ccdc.cam.ac.uk/data_request/cif.

16 Y. Cheng, B. Wang, X.-R. Wang, J.-H. Zhang and D.-C. Fang, *J. Org. Chem.*, 2009, **74**, 2357–2367.