Synthesis of Pyrroles in Supercritical Carbon Dioxide: Formal [3+2] Cycloaddition of 2-Benzoyl-Aziridines and Allenoates

Ana L. Cardoso, Rui M. D. Nunes, Luis G. Arnaut, Teresa M. V. D. Pinho e Melo*

Department of Chemistry, University of Coimbra, 3004-535 Coimbra, Portugal
Fax +351(239)827703; E-mail: tmelo@ci.uc.pt

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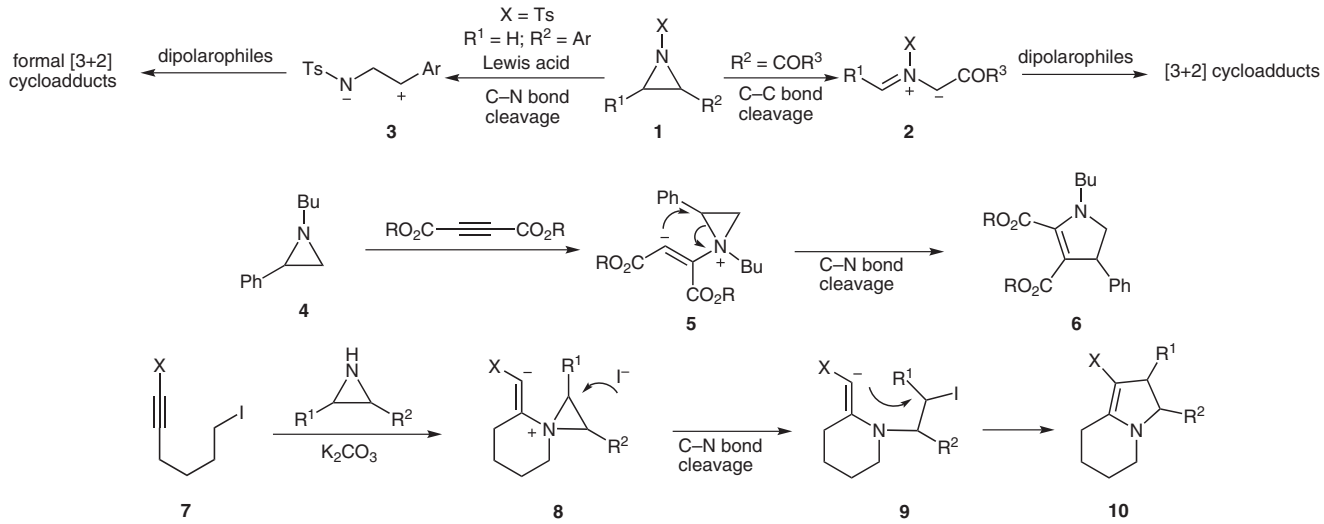
Dedicated to Prof. Francisco Palacios on the occasion of his 60th anniversary

Abstract: The reactivity of *N*-benzyl- and *N*-cyclohexyl-2-benzoyl-3-phenylaziridines toward allenoates in supercritical carbon dioxide ($scCO_2$) is described. The study led to the development of a sustainable and selective approach to pyrrole derivatives and gave a new insight into the mechanism involved in the process.

Key words: cycloaddition, $scCO_2$, aziridines, allenes, pyrroles

Aziridines are valuable strained small heterocycles that are of interest for preparative organic synthesis. In fact, chemistry based on the ring opening of aziridines has been used in an impressive range of synthetic applications.[1] Aziridines **1** undergo electrocyclic ring opening upon irradiation or thermolysis, giving azomethine ylides **2** through C–C bond cleavage, which participate in 1,3-dipolar cycloadditions to give five-membered nitrogen heterocycles.[1] On the other hand, in the presence of Lewis acids, *N*-tosylarylaziridines undergo C–N bond cleavage leading to zwitterionic 1,3-dipoles **3**, which react with alkenes, alkynes, ketones, and nitriles to form formal 1,3-dipolar cycloadducts.[2] Mattay et al. reported that the nonactivated aziridine **4** reacts with acetylenedicarboxylates affording a dipolar intermediate **5**, followed by an intramolecular attack of the carbanion on the aziridine ring to give the formal 1,3-dipolar cycloaddition product **6** through C–N bond cleavage.[3] A sequential S_N2/formal [3+2] cycloaddition approach to indolizines starting from non-activated aziridines has also been reported.[4] After the initial S_N2 reaction of 7-iodo-2-heptynoates **7** and N-unsubstituted aziridines, dipole **8** is formed. The reaction with iodide anion then leads to the opening of the aziridine ring[5] followed by a third S_N2 reaction giving the final products (Scheme 1).

We have recently described the results of studies on the reactivity of buta-2,3-dienoates toward aziridines (Scheme 2).[6] It was observed that allenoates can react as the 2-component in the [3+2] cycloaddition with azomethine ylides generated from aziridines, affording 4-methylenepyrrolidines, but they can also react via formal [3+2] cycloadditions leading to functionalized pyrroles. The substitution pattern of the aziridine determines the chemical behaviour of allenoates in the presence of these three-membered heterocycles. Site-, regio- and stereoselective synthesis of 4-methylenepyrrolidines **12** was achieved by [3+2] cycloaddition of allenoates with azomethine ylides generated from *N*-benzyl-2-benzoyl-3-phenylaziridine.



Scheme 1 Aziridines in [3+2] and formal [3+2] cycloadditions

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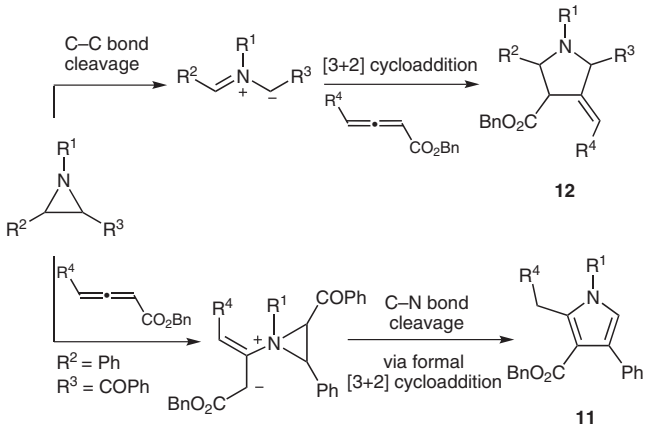
However, reactions of *N*-cyclohexyl- or *N*-*t*-butyl-2-benzoyl-3-phenylaziridines with buta-2,3-dienoates led to a different outcome. In these cases, pyrroles **11** were obtained as single or major products, resulting from formal [3+2] cycloadditions through aziridine C–N bond cleavage followed by a retro-aldol type fragmentation with elimination of benzaldehyde. From the reaction with allenoates bearing bulkier C-4 substituents, 4-methylenepyrrolidines were also formed as minor products.



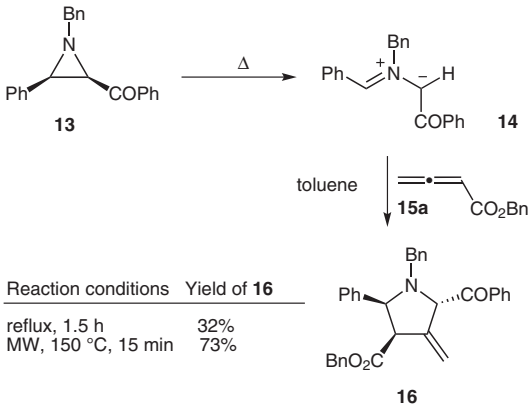
Scheme 2 Reactivity of aziridines toward allenoates

This study gave an insight into the chemistry of aziridines and provided a synthetic approach to nitrogen-containing five-membered heterocycles, which are among the most common structures in biologically active compounds, making them important target molecules.[7–9] Therefore, we decided to further explore the chemistry of aziridines toward allenoates with the aim of finding a more sustainable approach to this type of heterocycle.

Supercritical carbon dioxide ($scCO_2$) is regarded as an environmentally friendly solvent for organic synthesis, and is an attractive alternative to conventional organic solvents. The physical properties of $scCO_2$ are intermediate between the gas and the liquid phases and can be tuned by changing pressure and temperature.[10] In particular, changes close to the critical point enable drastic changes in density, viscosity and diffusion. Among supercritical fluids (SCF), $scCO_2$ has received special attention since it is readily accessible at a low critical temperature (T_c = 31 °C) and moderate critical pressure (P_c = 75.8 bar). Supercritical carbon dioxide is also a desirable organic solvent replacement because it is abundant, inexpensive, non-toxic, non-flammable and can be easily separated from the reaction mixture.

The use of SCF as a substitute for organic solvents has been exploited in a variety of organic reactions.[11–21] Due to higher solute diffusivity, lower fluid viscosity and a more limited solvation of reacting species than in liquid solvents, different kinetics can be observed in reactions carried out in $scCO_2$. Thus, the use of $scCO_2$ in processes under kinetic control can lead to enhanced selectivity.[22] In some cases, an improvement in selectivity can result from interactions between substrate and CO_2 or from simple solvent effects. In this paper, the study of the reactivity of *N*-benzyl- or *N*-cyclohexyl-2-benzoyl-3-phenylaziridines toward allenoates in $scCO_2$ is described.

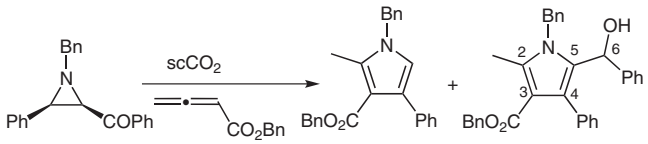
It has been previously reported that allenoate **15a** reacts as the 2-component in the [3+2] cycloaddition with azomethine ylide **14**, generated from *cis*-1-benzyl-2-benzoyl-3-phenylaziridine (**13**), giving 4-methylenepyrrolidine **16** selectively (Scheme 3).[6] Under conventional reaction conditions, this heterocycle was obtained as a single stereoisomer in moderate yield (32%). However, microwave-assisted 1,3-dipolar cycloaddition afforded the target molecule **16** in higher yield (73%).



Scheme 3 Aziridine **13** in the [3+2] cycloaddition with allenoate **15**[5]

The reactivity of aziridine **13** toward allenoate **15a** in $scCO_2$ was investigated (Table 1). Our study on the 1,3-dipolar cycloaddition of azomethine ylides generated from aziridines in $scCO_2$ indicated that the use of small amounts of co-solvents such as acetonitrile leads to more efficient processes.[21a] In fact, it has been demonstrated that the low polarity of $scCO_2$ can be a disadvantage but that this can be overcome by addition of very small amounts of co-solvent.[10] Thus, initial experiments were carried out using acetonitrile as co-solvent (Table 1, entries 1–5). Interestingly, the formation of 4-methylenepyrrolidine **16** was not observed. Performing the reaction with aziridine **13** (1.5 equiv) and allenoate **15a** at 90 °C with a CO_2 pressure of 100 bar for 18 hours, provided pyrrole **17a** in 69% yield as a single product (Table 1, entry 1). An improvement was achieved by carrying out the reaction at 80 °C with a shorter reaction time (4 h), giving the same pyrrole in 80% yield (Table 1, entry 2). However, when the reaction time was reduced to 2 h, pyrrole **17a** was formed as the major product (66%) together with pyrrole **18**, which was isolated in 9% yield (Table 1, entry 3). The reaction of aziridine **13** with allenoate **15a** in $scCO_2$ at 75 bar, 80 °C for four hours also led to the formation of pyrroles **17a** and **18** in 65 and 4% yield, respectively (Table 1, entry 4). A similar result was obtained using 1.0 equiv of aziridine instead of 1.5 equiv (Table 1, entry 5).

Table 1 Reaction of Aziridine **13** with Allenoate **15a** in $scCO_2$



13 **15a** **17a** **18**

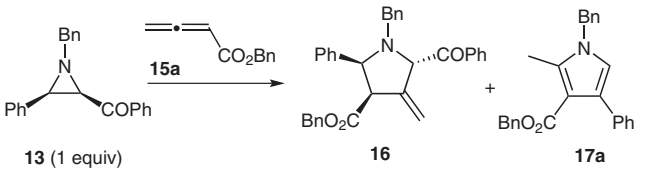
Entry	**13** (equiv)	MeCN (μL)	P (bar)	Temp (°C)	Time (h)	Products (%)[a] **17a**	**18**
1	1.5	520	100	90	18	69	–
2	1.5	520	90	80	4	80	–
3	1.5	520	100	80	2	66	9
4	1.5	520	75	80	4	65	4
5	1.0	520	98	83	4	62	5
6	1.5	–	85	90	4	79	–
7	1.5	–	100	80	4	50	31
8	1.0	–	90	85	4	64	–
9	1.0	–	100	80	4	64	3
10[b]	1.0	–	100	80	2	45	15
11	1.0	–	100	40	4	–	–
12	1.0	–	100	60	4	–	–

[a] Yield of isolated products.
[b] Starting aziridine and allenoate recovered.

The structural assignment of compound **18** was supported by two-dimensional, NOESY, HMQC and HMBC spectra (400 MHz). The HMBC spectrum shows connectivity of the methyl protons with C-3, and H-6 shows connectivity with C-4 and C-5, but no connectivity with C-3. In the NOESY spectrum, H-6 shows connectivity with the methylenic protons of the *N*-benzyl group, but no connectivity with the methylenic protons of the benzyl ester group. On the other hand, the infrared spectrum clearly shows a strong broad absorption band at 3450 cm^{-1}, which is characteristic of the hydroxy group.

It was important to determine whether the use of a co-solvent was necessary to assure the efficiency of this type of reaction. The reaction of aziridine **13** (1.5 equiv) with allenoate **15a** at 85 bar and 90 °C with a reaction time of four hours gave pyrrole **17a** in 79% yield as a single product (Table 1, entry 6). Thus, we could conclude that supercritical carbon dioxide is a very efficient medium for the synthesis of pyrrole **17a**. However, in the absence of co-solvent, when the reaction was carried out at 100 bar and 80 °C, pyrroles **17a** and **18** were obtained in 50 and 31% yield, respectively (Table 1, entry 7). We then studied this reaction without the addition of co-solvent using 1.0 equiv of aziridine. When the reaction was performed at 90 bar and 85 °C for four hours, pyrrole **17a** was isolated in 64% yield (Table 1, entry 8), whereas when the reaction was carried out at 100 bar and 80 °C, pyrroles **17a** and **18** were obtained (Table 1, entries 9 and 10). Attempts were also made to find reaction conditions that favour the formation of pyrrole **18**, namely, the use of lower temperature. However, no reaction was observed either at 40 or 60 °C (Table 1, entries 11 and 12). Thus, in contrast to the reaction in toluene of *N*-benzyl-2-benzoyl-3-phenylaziridine (**13**) with allenoate **15a**, which leads to 4-methylenepyrrolidine **16** (Scheme 3), the main reaction pathway in $scCO_2$ under the studied reaction conditions afforded pyrrole **17a** (Table 1).

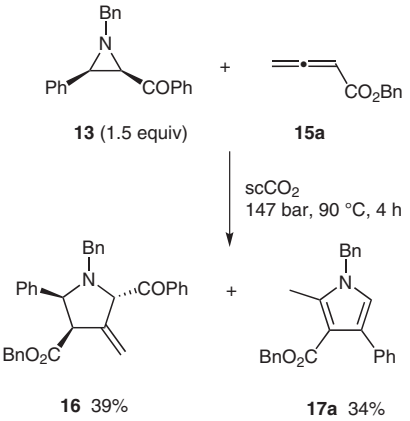
Table 2 Reaction of Aziridine **13** with Allenoate **15a**



13 (1 equiv) **16** **17a**

Entry	Reaction conditions	Products (%)[a] **16**	**17a**
1	Reflux, MeCN, 1.5 h	7[b]	11[b]
2	MW, MeCN, 110 °C, 15 min	12[c]	9[c]
3	$scCO_2$, toluene, 90 bar, 80 °C, 4 h	28	22
4	$scCO_2$, toluene, 140 bar, 80 °C, 4 h	2	48
5	$scCO_2$, MeOH, 100 bar, 80 °C, 2 h	–	63

[a] Yield of isolated products.
[b] Starting aziridine (47%) recovered.
[c] Starting aziridine (13%) and allenoate (25%) recovered.

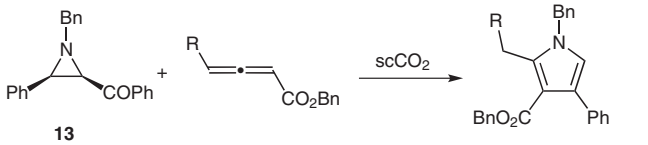


Scheme 4 Aziridine **13** in the [3+2] and formal [3+2] cycloaddition with allenoate **15**

These results suggest that the nature of the solvent may have a role in determining the reaction outcome. Therefore, reactions under conventional thermolysis and under microwave irradiation were carried out using acetonitrile as solvent. In both cases, 4-methylenepyrrolidine **16** and pyrrole **17a** were obtained in low overall yield (Table 2, entries 1 and 2). Thus, on changing the solvent from toluene to acetonitrile, although the process becomes less efficient, it was observed that the synthesis of pyrrole **17a**

becomes more favourable. The reaction carried out in $scCO_2$ at 90 bar and 80 °C for four hours using toluene as co-solvent gave 4-methylenepyrrolidine **16** and pyrrole **17a** in 28 and 22% yield, respectively (Table 2, entry 3). It should be mentioned that similar reaction conditions in $scCO_2$ in the absence of co-solvent or in the presence of acetonitrile lead to the formation of pyrrole **17a**, and pyrrolidine **16** was never observed (Table 1, entries 2 and 8). At higher CO_2 pressure (140 bar), pyrrole **17a** was formed as the major product (48%), whereas pyrrolidine **16** was isolated in 2% yield (Table 1, entry 4). Using methanol as co-solvent, pyrrole **17a** was obtained in 63% yield as a single product (Table 1, entry 5).

Table 3 Synthesis of Pyrroles **17b–d** in $scCO_2$ from the Reaction of Aziridine **13** with Allenoates **15b–d**



15b R = Ph
15c R = Me
15d R = Bn
15e R = *t*-Bu

17b R = Ph
17c R = Me
17d R = Bn

Entry	R	**13** (equiv)	MeCN (μL)	P (bar)	Temp (°C)	Time (h)	Product	Yield (%)[a]
1	Ph	1.5	520	118	82	4	**17b**	79
2	Ph	1.0	–	100	80	2	**17b**	63[b]
3	Me	1.0	520	115	80	2	**17c**	7
4	Me	1.0	520	110	80	4	**17c**	18
5	Bn	1.5	520	95	82	4	**17d**	58
6	*t*-Bu	1.0	520	100	80	2	–	–
7	*t*-Bu	1.0	520	100	80	19	–	–

[a] Yields of isolated product.
[b] Starting aziridine and allenoate recovered.

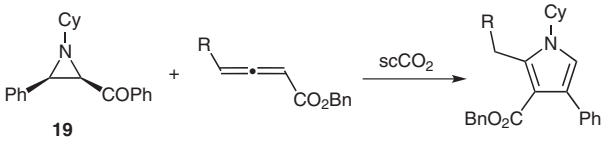
The described results indicate that the best reaction conditions for selective generation of pyrrole **17a** involve the reaction of aziridine **13** and allenoate **15a** in $scCO_2$ at 85 bar and 90 °C (Table 1, entry 6). Interestingly, when the $scCO_2$ pressure was raised to 147 bar, both cycloaddition via azomethine ylide **14** and formal [3+2] cycloaddition took place, affording pyrrolidine **16** and pyrrole **17a** in 39 and 34% yields, respectively (Scheme 4). Therefore, the selectivity towards pyrrole **17a** is higher at pressures close to the critical pressure of $scCO_2$.

The work was extended to reactions of aziridine **13** with allenoates **15b–d** in $scCO_2$ (Table 3). Using CO_2 pressures between 95 and 118 bar, the corresponding pyrroles **17** were obtained as a single product. Pyrrole **17b** was isolated in good yield either using acetonitrile as co-solvent or in the absence of a co-solvent (Table 3, entries 1 and 2). The reaction of aziridine **13** with allenoate **15d** also efficiently led to the formation of pyrrole **17d**[6b] in 58% yield (Table 3, entry 5). However, pyrrole **17c** could only be obtained in low yield (Table 3, entries 3 and 4). In the reaction of aziridine **13** with allenoate **15e**, bearing a bulky C-4 substituent, no reaction was observed (Table 3, entries 6 and 7).

Aiming to find out whether the nature of the N-substituent of the 2-benzoyl-3 phenylaziridines plays a role in the chemical behaviour of these three-membered heterocycles in the presence of allenoates, *cis*-2-benzoyl-1-cyclohexyl-3-phenylaziridine (**19**) was synthesized and its reactivity toward allenoates in $scCO_2$ was studied (Table 4). Aziridine **19** reacted with allenoate **15a** at 100 bar and 80 °C for four hours using acetonitrile as co-solvent, giving pyrrole **20a**[6b] in moderate yield; an improvement was achieved with a longer reaction time (18 h), affording the product in 40% yield (Table 4, entries 1 and 2). However, the same pyrrole could be obtained in higher yield (58%) in the absence of co-solvents at 90 bar and 85 °C for four hours (Table 4, entry 3). It was observed that the best reaction conditions for the synthesis of pyrroles **20b–d**[6b] from the reaction of aziridine **19** and the appropriate allenoate was also the use of $scCO_2$ without co-solvent as the reaction medium (Table 4, entries 4–8). It has been reported that aziridines can be converted into 2-oxazolidinones under $scCO_2$.[23] However, adducts of this type were never detected in the studied reactions of aziridines **13** and **19** with allenoates.

We have previously proposed that pyrroles can be obtained from aziridines and allenoates via a formal [3+2] cycloaddition as outlined in Scheme 5.[6] Nucleophilic addition of the aziridine to the activated allenoate double

Table 4 Synthesis of Pyrroles **20** from the Reaction of Aziridine **19** with Allenoates



15a R = H
15b R = Ph
15c R = Me
15d R = Bn

20a R = H
20b R = Ph
20c R = Me
20d R = Bn

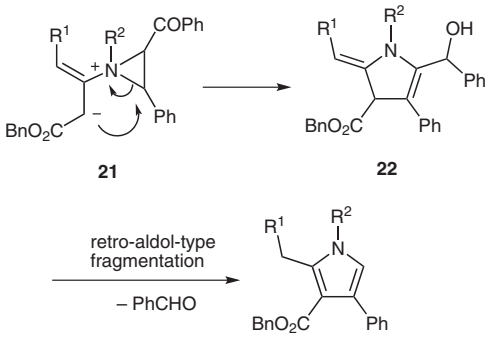
Entry	R	MeCN (μL)	P (bar)	Temp (°C)	Time (h)	Product	Yield (%)[a]
1	H	520	100	80	4	**20a**	21
2	H	520	110	80	18	**20a**	40
3	H	–	90	85	4	**20a**	58
4	Ph	520	90	80	18	**20b**	34
5	Ph	–	110	80	4	**20b**	51
6	Me	–	110	80	4	**20c**	49
7	Bn	520	90	80	18	**20d**	37
8	Bn	–	90	85	4	**20d**	70

[a] Yields of isolated products.

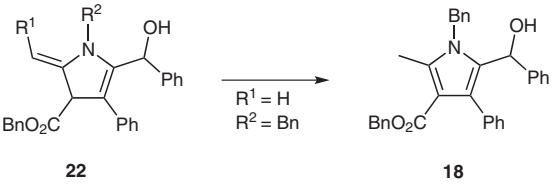
bond giving intermediate **21** followed by intramolecular attack of the carbanion centre on the aziridine ring, affords the five-membered heterocycles via C–N bond cleavage. Tautomerisation leads to the formation of pyrrole **22**, bearing a hydroxybenzyl side-chain, which is converted into the final product and benzaldehyde via retro-aldol type fragmentation.

The isolation of pyrrole **18** from the reaction of aziridine **13** and allenoate **15a** (Table 1) supports the mechanistic proposal. The formation of this derivative can be explained by considering that the proposed intermediate **22** is formed and undergoes tautomerisation to give the corresponding pyrrole containing a hydroxybenzyl substituent (Scheme 6). On the other hand, the isolation of benzaldehyde from reactions where pyrroles **17** and **20** were obtained is in agreement with the proposed final step involving a retro-aldol type fragmentation.

The work reported herein has demonstrated that the use of $scCO_2$ medium favours this type of formal [3+2] cycloaddition. In fact, even in cases where aziridines and allenoates participate exclusively in 1,3-dipolar cycloadditions in organic solvents (via the generation of azomethine ylides in situ) to give 4-methylenepyrrolidines (e.g., reaction of aziridine **13** in toluene with allenoates **15a–c**[6]), the reaction in $scCO_2$ with pressures between 75–100 bar allowed the exclusive synthesis of pyrroles **17** (Table 1 and Table 3). The exclusive formation of pyrroles **17** and **20** was also observed when the reaction was conducted in $scCO_2$ using acetonitrile or methanol as co-solvents. However, using $scCO_2$ with the addition of minute amounts of toluene in the reaction of aziridine **13** and allenoate **15a** led to the competitive synthesis of 4-methylenepyrrolidine and pyrrole derivatives. The reaction of aziridine **13** with allenoate **15a** at a $scCO_2$ pressure of 147 bar, in the absence of a co-solvent, afforded both pyrrole **17a** and pyrrolidine **16**. Thus, there is an intrinsic advantage of using $scCO_2$ as solvent near the critical pressure. The higher solute diffusivity, lower fluid viscosity, and limited solvation of reacting species than in liquid solvents is lost when $scCO_2$ pressure is increased. These observations indicate that solvent effects near the critical point can play an important role in determining the outcome of this type of reaction.



Scheme 5 Mechanism proposal for the formal [3+2] cycloaddition of aziridines and allenotes



Scheme 6 Mechanism proposal for the synthesis of pyrrole **18**

In conclusion, we have described the selective synthesis of pyrroles in $scCO_2$ from the reaction of 2-benzoyl-aziridines with allenoates. In contrast to the reactivity observed in toluene, the main pathway involves a formal [3+2] cycloaddition starting either from *N*-benzyl- or *N*-cyclohexyl-2-benzoyl-3-phenylaziridines.

The isolation, under selected reaction conditions, of a minor amount of the pyrrole derivative containing a hydroxybenzyl side-chain, which is formed from a proposed intermediate, reinforced the mechanism proposal. Furthermore, the isolation of benzaldehyde from these reactions is also in agreement with the proposed final step involving a retro-aldol type fragmentation.

^{1}H NMR spectra were recorded with a Bruker Avance III instrument operating at 400 MHz; ^{13}C spectra were recorded with a Bruker Avance III instrument operating at 100 MHz. Spectra were recorded with samples dissolved in $CDCl_3$, except where otherwise indicated. Mass spectra were recorded under electrospray ionization (ESI) except where indicated otherwise. Compounds **16**, **17d** and **20c–d** were prepared following the general procedure described below and were identified by comparison with specimens previously prepared.[6] Buta-2,3-dienoates **15** were prepared through Wittig reaction of benzyl(triphenylphosphoranylidene)acetate with ketenes following known synthetic procedures.[24] *cis*-1-Benzyl-2-benzoyl-3-phenylaziridine (**13**) and *cis*-2-benzoyl-1-cyclohexyl-3-phenylaziridine (**19**) were prepared by a known procedure.[25,6]

Reactions in Supercritical Carbon Dioxide; Reaction Setup and General Procedure

CO_2 (airliquide, N48) was passed through an Alltech charcoal trap and a Matheson Tri-Gas oxygen absorbing purifier (model 6410), before being allowed into the high-pressure reactor specifically built in our laboratory (V = 55 cm^3). The reactor body was made of stainless steel and the upper part was sealed with a Teflon ring and bolted against the reactor body in a circular cage drilled into the stainless steel. The reactor was fitted with two external connections via 1/16″ stainless steel tubes. One was connected through a valve to the high-pressure inlet system, and the other to a digital pressure indicator (Omega DP20 and Schaevitz pressure sensor, precision ±0.25%). A magnetic stirrer placed inside the reactor kept the solutions homogeneous during the reaction. The temperature was measured using a thermopar sensor inserted through a hole drilled in the upper part of the reactor.

In a typical procedure, allene (1 equiv, 0.171 mmol) was introduced into the reactor together with aziridine (1 or 1.5 equiv) and MeCN (520 μL), and the reactor was closed and connected to a high-pressure line. The reactor was cooled to –80 °C and all air was pumped out during 30 min and then pressurized with CO_2. The reactor was then placed in a thermostatic bath (water or paraffin) at the appropriate temperature and the reaction was stirred for 4 h.

Benzyl 1-Benzyl-2-methyl-4-phenyl-1*H*-pyrrole-3-carboxylate (17a) and Benzyl 1-Benzyl-5-(1′-hydroxy-1′-phenylmethyl)-2-methyl-4-phenyl-1*H*-pyrrole-3-carboxylate (18)

Prepared by the general procedure from aziridine **13** and allene **15a**. Purification by preparative thin layer chromatography (EtOAc–hexane, 1:10) afforded **17a** (1st eluted compound) and **18** (2nd eluted compound).

Compound 17a

Yellow oil.

IR (film): 1700, 1653, 1522, 1497, 1454 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 2.47 (s, 3 H), 5.04 (s, 2 H), 5.15 (s, 2 H), 6.56 (s, 1 H), 7.08–7.33 (m, 15 H, ArH).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.6, 50.6, 65.3, 110.8, 120.5, 125.5, 126.2, 126.4, 126.6, 127.6, 127.8, 128.0, 128.2, 128.9, 129.4, 135.9, 136.4, 136.7, 136.8, 165.6.

MS (ESI): *m*/*z* (%) = 381 (48) $[M]^+$, 290 (29), 272 (45), 91 (100).

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd. for $C_{26}H_{24}NO_2$: 382.18072; found: 382.18016.

Compound 18

Orange oil.

IR (film): 3450, 1697, 1452 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 2.22 (s, 3 H), 4.78 (s, 2 H), 4.96 (s, 2 H), 5.98 (s, 1 H), 6.57–6.59 (m, 2 H, ArH), 6.84–6.86 (m, 2 H, ArH), 7.05–7.19 (m, 16 H, ArH).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.2, 48.3, 65.2, 67.1, 112.7, 121.0, 125.6, 127.1, 127.8, 127.9, 128.2, 128.3, 128.5, 132.5, 136.3, 138.4, 140.2, 141.7, 165.3.

MS (ESI): *m*/*z* (%) = 488 (15) $[M + H]^+$, 470 (100), 447 (9), 382 (15).

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd. for $C_{33}H_{30}NO_3$: 488.22156; found: 488.22202.

Benzyl 1,2-Dibenzyl-4-phenyl-1*H*-pyrrole-3-carboxylate (17b)

Prepared by the general procedure from aziridine **13** and allene **15b**. Purification by preparative thin layer chromatography (EtOAc–hexane, 1:10) afforded **17b**.

Yellow oil.

IR (film): 1695, 1603, 1496, 1459 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 4.35 (s, 2 H), 4.90 (s, 2 H), 5.14 (s, 2 H), 6.57 (s, 1 H), 6.98–7.39 (m, 20 H, ArH).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 31.0, 50.6, 65.4, 111.9, 121.2, 126.2, 126.3, 126.5, 126.7, 127.6, 127.7, 127.8, 128.0, 128.1, 128.2, 128.6, 128.9, 129.4, 135.8, 136.2, 136.6, 137.9, 138.6, 165.4.

MS (ESI): *m*/*z* (%) = 458 (100) $[M + H]^+$, 448 (40), 415 (13), 350 (15).

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd. for $C_{32}H_{28}NO_2$: 458.21354; found: 458.21146.

Benzyl 1-Benzyl-2-ethyl-4-phenyl-1*H*-pyrrole-3-carboxylate (17c)

Prepared by the general procedure from aziridine **13** and allene **15c**. Purification by preparative thin layer chromatography (EtOAc–hexane, 1:10) afforded **17c**.

Yellow oil.

IR (film): 1700, 1653, 1604, 1521, 1497, 1456 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 1.10 (t, *J* = 7.6 Hz, 3 H), 2.93 (q, *J* = 7.6 Hz, 2 H), 5.08 (s, 2 H), 5.16 (s, 2 H), 6.52 (s, 1 H), 7.07–7.35 (m, 15 H, ArH).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.3, 19.0, 50.3, 65.3, 109.9, 120.5, 126.1, 126.6, 127.6, 127.8, 128.1, 128.2, 128.4, 128.6, 128.7, 128.9, 129.4, 133.8, 135.9, 136.4, 137.0, 165.3.

MS (ESI): *m*/*z* = 396 (100) $[M + H]^+$, 339 (37), 314 (7), 279 (4).

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd. for $C_{27}H_{26}NO_2$: 396.19565; found: 396.19581.

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