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Single and Consecutive Cyclization Reactions of Alkynyl Carbene Complexes and 8-Azaheptafulvenes: Direct Access to Polycyclic Pyrrole and Indole Derivatives

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Abstract: The reactivity of alkynyl and enynyl Fischer carbene complexes towards 8-azaheptafulvenes is examined. Alkynyl carbenes **1a–f** undergo regioselective [8+2] heterocyclization with 8-aryl-8-azaheptafulvenes **2a**,**b** providing cycloheptapyrroles **3** and **4** with metal carbene or ester functionality at C3. Moreover, consecutive cyclization reactions are involved when enynyl carbenes are used. Thus, the cyclopenta[*b*]pyrrole framework **7** is formed by the consecutive [8+2] cyclization and cyclopentannulation reactions. The initially formed cyclopentannulation adduct can be intercepted through a Diels–Alder reaction with classic dienophiles to afford increasing structural complexity (compounds **8** and **9**). More importantly, the construction of the indole skeleton is accomplished with a high degree of substitution and functionalization (compounds **11**–**15**) by a one-pot sequence that involves [8+2] cyclization, R−NC or CO insertion, and ring closure.

Keywords: carbenes · chromium · cyclization · heterocycles · indole · pyrrole

Introduction

Cyclization reactions involving α,β-unsaturated Fischer carbene complexes (FCCs) have been a focus of great attention in the past years, mostly owing to their rich and versatile reactivity that makes them interesting starting materials for the construction of cyclic molecules of different types.[1] First of all, the strong activation of the conjugated carbon–carbon double and triple bond by the metal–carbene function has been exploited for selective [4+2][2] and [3+2][3] cycloaddition reactions. Moreover, the resulting carbene cycloadducts can occasionally undergo further cyclization, thus increasing the structural complexity of the reaction product.[4] On the other hand, when the metal–carbon bond is involved in the cyclization process, the unsaturated carbene ligand can participate as a one-[5], three-[6], and five-carbon[7] synthesis equivalent.[8]

Despite the fact that much work has been devoted to carbocylization reactions, the cyclization of FCCs with heteroatom-containing substrates leading to heterocyclic systems has been studied to a lesser extent.[9] Thus, apart from some examples of cycloaddition reactions with 1,3-dipoles through the activated carbon–carbon bond,[3] imines and unsaturated imines have been the substrates most-commonly reported for heterocyclization of FCCs. Although simple imines undergo diastereo- and enantioselective [3+2] cyclization with enantiopure alkenyl carbene complexes ($3C_{carbene}$ + C,N_{imine}) to provide pyrrolidinone derivatives,[10] the [4+2] and the [4+3] cycloaddition reactions were observed in the case of α,β-unsaturated imines and alkynyl carbenes affording dihydropyridines ($3C,N_{imine}$ + $2C_{carbene}$)[11] and azepinones ($3C,N_{imine}$ + $3C_{carbene}$),[12] respectively.

Looking for a different heteroatom substrate, for instance the unusual two-carbon, one-nitrogen synthon (2C,N), we have recently found that the 8-azaheptafulvene system represents an appropriate model towards high-order cyclization reactions of Fischer alkenyl carbene complexes to provide fused pyrrolidine and piperidine derivatives ([8+2] and [8+3] cyclization reactions, respectively; Scheme 1).[13]

Keeping these precedents in mind as well as 1) alkynyl carbene complexes are very prone to react through the activated C≡C bond, 2) the known ability of alkenyl-conjugated alkynyl carbene complexes to develop consecutive cyclization reactions, 3) a sole cycloaddition of 8-azaheptafulvenes

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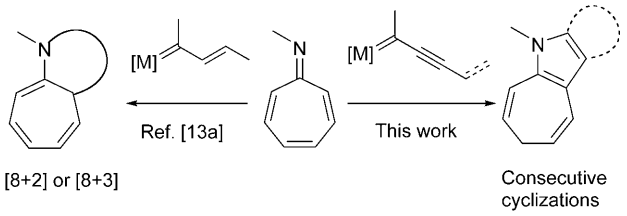


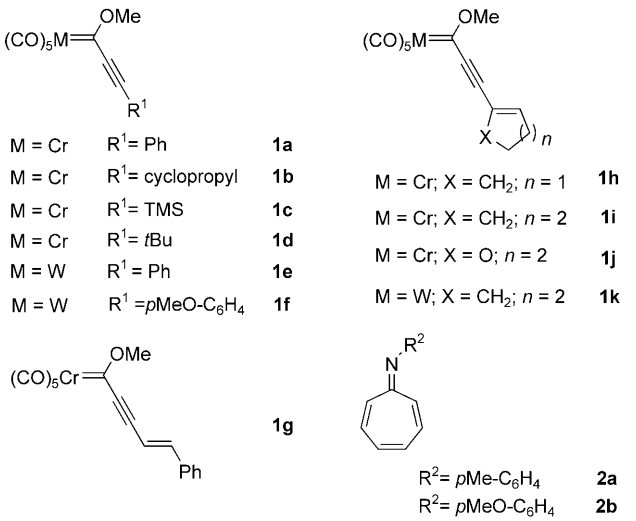
Scheme 1. Cyclization reactions of 8-azaheptafulvenes with alkenyl and alkynyl Fischer carbene complexes.

with a strongly activated alkyne has been described as yet,[14] we have studied the reaction of Fischer alkynyl and enynyl carbene complexes with *N*-aryl-8-azaheptafulvenes. Herein, we report on the construction of the pyrrole unit by the single [8+2] cyclization as well as of fused pyrroles, for example, the indole framework by consecutive [8+2] cyclization/benzoannulation reactions (Scheme 1). The structure of all the metal–carbene complexes **1** (alkynyl carbenes **1a**–**f**; enynyl carbenes **1g**–**k**) and 8-azaheptafulvenes **2a**,**b** employed are depicted in Scheme 2.

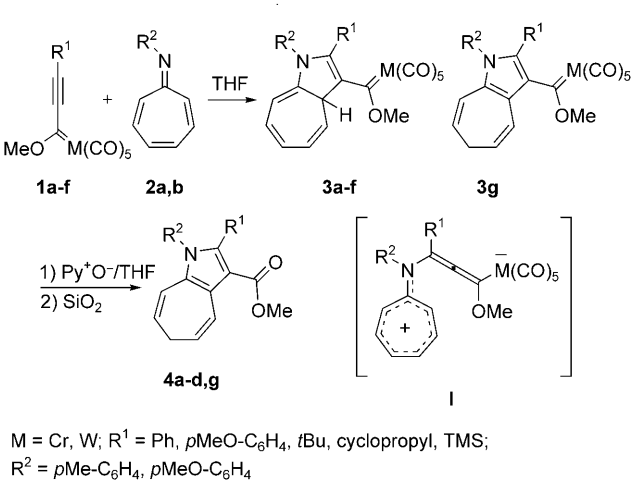
Results and Discussion

[8+2] Cycloaddition of alkynyl carbene complexes 1a–f with 8-aryl-8-azaheptafulvenes 2: First, chromium alkynyl carbene **1a** (R^1=Ph) was mixed with 8-azaheptafulvene **2a** (R^2=*p*Me-C_6H_4; 1:1 molar ratio) in THF and the mixture was stirred for 3 h at room temperature. Removal of the solvent and purification of the residue by column chromatography (SiO_2, hexanes/EtOAc 50:1) allowed the isolation of the 1,3a-dihydrocyclohepta[*b*]pyrrole carbene complex **3a** in 84% yield (Scheme 3; Table 1, entry 1).[15] The scope of this [8+2] cycloaddition reaction was studied by using chromium–carbene complexes with representative substitution pat-

Abstract in Spanish: *Se ha estudiado la reactividad de alquinil y eninil complejos carbeno de Fischer frente a 8-azaheptafulvenos. Los alquinil carbenos **1a–f** experimentan una heterociclación [8 + 2] frente a 8-aril-8-azaheptafulvenos **2a–b** dando lugar a cicloheptapirroles **3** y **4** conteniendo en C-3 una función metal carbeno o éster. Además, cuando se usan eninilcarbenos se producen reacciones consecutivas de ciclación. Así, mediante reacciones consecutivas de ciclación [8 + 2] y ciclopentanulación, se forma el esqueleto de ciclopenta[b]pirrol **7**. El aducto de ciclopentanulación formado inicialmente puede ser atrapado mediante una reacción Diels–Alder con dienófilos clásicos, dando lugar a una mayor complejidad estructural (compuestos **8** y **9**). De mayor interés es el hecho de que se pueda llevar a cabo la construcción del esqueleto de indol con alto grado de sustitución y funcionalización (compuestos **11–15**) mediante una secuencia "one-pot" que implica una ciclación [8 + 2], inserción de R-NC o CO y cierre de anillo.*



Scheme 2. Carbene complexes **1** and 8-azaheptafulvenes **2** used in this work.



Scheme 3. The [8+2] cycloaddition of Fischer carbene complexes **1a**–**f** and 8-azaheptafulvenes **2**.

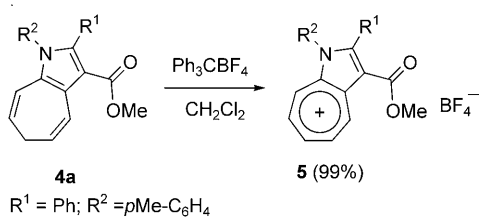
Table 1. Carbene cycloadducts **3** and esters **4** from carbenes **1** and azaheptafulvenes **2**.

Entry	1	2	Cr	R^1	R^2	Product	Yield [%][a]
1	**1a**	**2a**	Cr	Ph	*p*Me-C_6H_4	**3a**	84
						4a[b]	72
2	**1b**	**2a**	Cr	cyclopropyl	*p*Me-C_6H_4	**3b**	75
						4b[b]	69
3	**1c**	**2a**	Cr	TMS	*p*Me-C_6H_4	**3c**	69
						4c[b]	70
4	**1d**	**2a**	Cr	*t*Bu	*p*Me-C_6H_4	**3d**	78
						4d	80
5	**1e**	**2a**	W	Ph	*p*Me-C_6H_4	**3e**	80
6	**1f**	**2a**	W	*p*MeO-C_6H_4	*p*Me-C_6H_4	**3f**	88
7	**1e**	**2b**	W	Ph	*p*MeO-C_6H_4	**3g**	64
						4g	87

[a] Overall yields after purification with column chromatography (silica gel, hexanes/EtOAc 50:1). [b] Obtained as major compound along with the 1,4-dihydrocyclohepta[*b*]pyrrole isomer

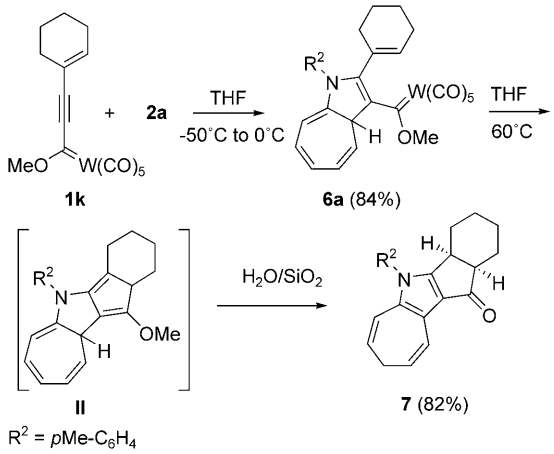
terns, such as carbenes **1b–d** (R^1 = cyclopropyl, trimethylsilyl (TMS), *t*Bu). In this way, the new carbene complexes **3b–d** were obtained in good yields (69–78%) after purification by chromatography (Scheme 3; Table 1, entries 2–4). On the other hand, the [8+2] cycloaddition by using tungsten–carbene complexes **1e** and **1f** took place under the same reaction conditions to produce the tungsten–carbene complexes **3e–f** (80–88% yield; Table 1, entries 5 and 6). Moreover, the cyclization between the 8-azaheptafulvene with a removable substituent (**2b**; R^2 = *p*MeO-C_6H_4)[16] and the carbene **1e** led to the 1,6-dihydrocyclohepta[*b*]pyrrole carbene isomer **3g** albeit in a lower yield (64%; Table 1, entry 7).[15] The course of this [8+2] cyclization can be rationalized by the nucleophilic conjugate addition through the lone pair on the nitrogen atom to the electrophilic alkynylcarbene to form the zwitterionic intermediate **I**, which cyclizes though attack of the metal allenyl metallate to the tropilium cation.

Next, the oxidation of the resulting carbenes **3a–d,g** to the corresponding esters **4** was achieved in good yield (69–87%) with pyridine oxide (THF, 25°C, 1 h; Scheme 3; Table 1, entries 1–4,7). Notably, the 1,3a-dihydrocyclohepta[*b*]pyrrole skeleton of the starting metal carbenes **3a–d** undergoes isomerization during chromatographic purification to the more stable 1,6-dihydrocyclohepta[*b*]pyrrole esters **4a–d** (SiO_2, hexanes/EtOAc 50:1). In addition, minor amounts of the isomeric 1,4-dihydrocyclohepta[*b*]pyrrole esters (<15%) were formed and separated in most cases.[15] Finally, compound **4a** was aromatized by hydride abstraction with trityl tetrafluoroborate to provide the pyrrole-fused tropylium salt **5** (99% yield; Scheme 4).



Scheme 4. Aromatization of **4a** to the tropilium salt **5**.

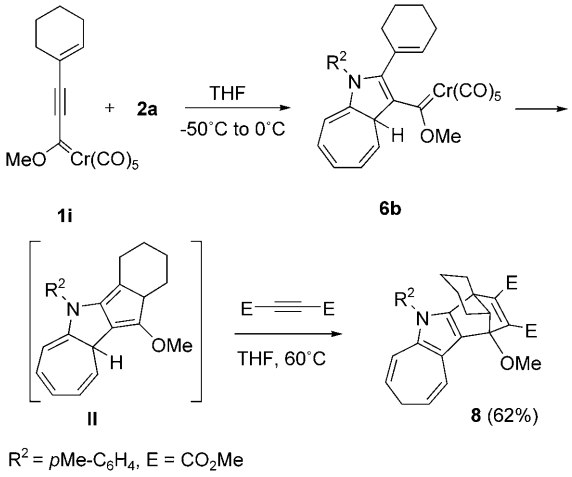
Consecutive [8+2] cyclization/cyclopentannulation reactions of enynyl carbene complexes 1i and 1k with 8-azaheptafulvene 2a: Frequently, the cyclization of alkynylcarbenes can be extended beyond a single cyclization if a conjugated alkenyl substituent is present in the starting metal carbene.[17] In such a case, the corresponding cycloadducts **3** would feature the 1-metalla-1,3,5-hexatriene function (see Scheme 3; R^1 = alkenyl in compounds **3**) amenable for further diverse cyclizations. First, it was noted that running the reaction of azaheptafulvene **2a** with the tungsten cyclohexenylethynyl carbene **1k** under the reaction conditions described above (THF, room temperature) led to a complex mixture of unidentified compounds. Satisfactorily, the reaction worked well if the reagents were mixed at −50°C and the resulting mixture slowly warmed up to 0°C. In this way, the expected tungsten–carbene cycloadduct **6a** was obtained in 84% yield after removal of solvent and column chromatography purification (SiO_2, hexanes/EtOAc 10:1; Scheme 5).



Scheme 5. Consecutive [8+2] cycloaddition and cyclopentannulation of carbene **1k** and azaheptafulvene **2a**.

Compound **6a** was then subjected to thermal cyclization (refluxing THF, 3 h) to furnish the tetracyclic ketone **7** in 82% yield after column chromatography (SiO_2, hexanes/EtOAc 10:1). This cyclopentannulation most probably involves electrocyclization of the metallatriene fragment and reductive metal elimination (intermediate **II**), followed by SiO_2-promoted hydrolysis of the enol ether (Scheme 5).[15]

On the other hand, the chromium cycloadduct carbene **6b** was formed from carbene **1i** under the above reaction conditions as established by ^{1}H NMR spectroscopy of the crude (Scheme 6). However, unlike the analogous tungsten carbene **6a**, this chromium carbene was too unstable to be purified. Moreover, attempts to induce the thermal cyclopentannulation reaction by stirring crude **6b** failed owing to de-



Scheme 6. Formation and Diels–Alder reaction of the cyclopentannulation intermediate **II** with dimethyl acetylenedicarboxylate.

composition even at room temperature. At this point, we were interested to know whether the cyclopentannulation to the intermediate **II** had occurred prior to decomposition. To prove this, the carbene **1i** and the azaheptafulvene **2a** were allowed to form **6b** (THF, −50 to 0°C) and then dimethyl acetylenedicarboxylate was added to the reaction mixture and heated at 60°C for 12 h. Removal of the solvent and purification through column chromatography of the resulting mixture (SiO_2, hexanes/EtOAc 3:1) afforded compound **8** in 62% overall yield (Scheme 6). Therefore, the initial carbene cycloadduct **6b** does undergo the cyclopentannulation reaction to generate the cyclopentadiene structure **II**, which in turn yields the [4+2] cycloadduct **8** upon reaction with dimethyl acetylenedicarboxylate (Scheme 6).The structure of **8** was elucidated by NMR analysis and confirmed by X-ray diffraction analysis (Figure 1).[18]

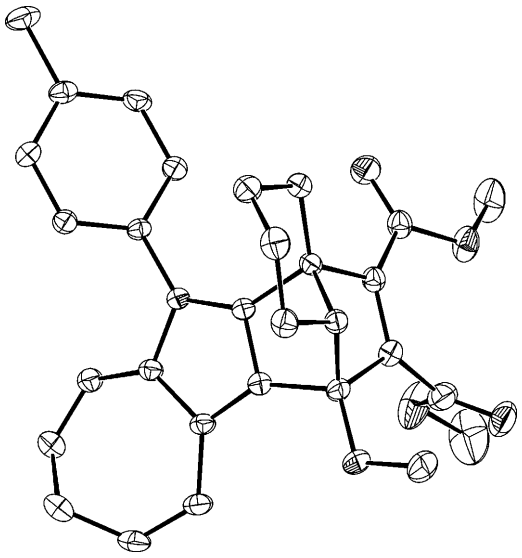
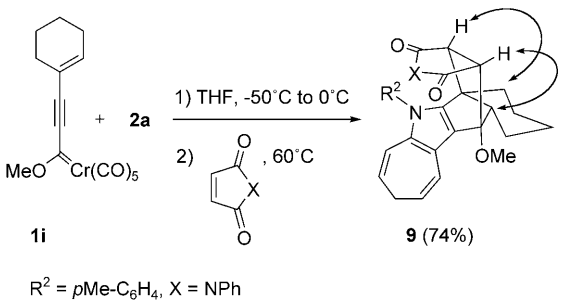


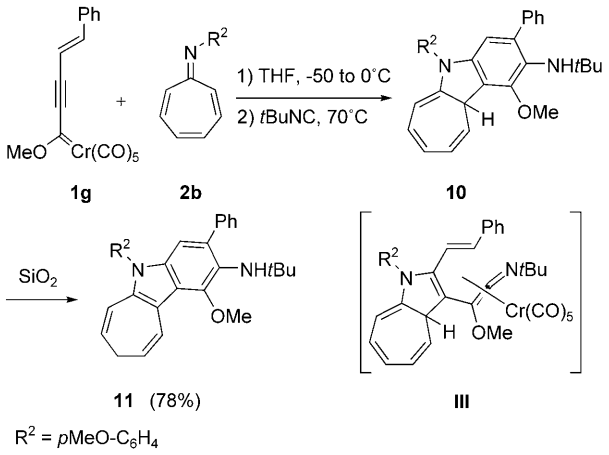
Figure 1. X-ray structure for compound **8** in the crystal. Thermal ellipsoids at the 50% probability level.

In the same way, the one-pot multicyclization process with maleinimide as the dienophile afforded compound **9** in 74% yield, wherein five stereogenic centers were created consecutively with complete diastereoselectivity (Scheme 7).[19] The structure of **9** was determined by NMR spectroscopic experiments and the relative configuration assigned by NOESY experiments.



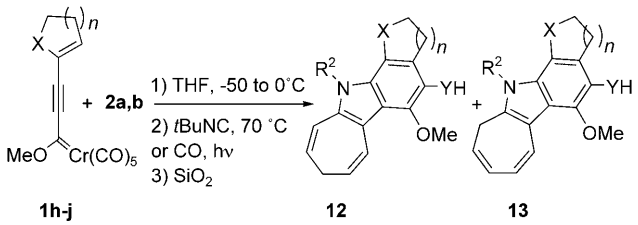
Scheme 7. One-pot formation of **9** from **1i** and **2a** by a [8+2] cycloaddition/cyclopentannulation/[4+2] cycloaddition sequence.

Consecutive [8+2] cyclization/benzoannulation reactions of chromium enynyl carbene complexes 1g–j with 8-azaheptafulvenes 2: Synthesis of substituted indoles: The usefulness of the [8+2] cyclization of alkynyl Fischer carbenes and 8-azafulvenes can be extended to the synthesis of heteropolycyclic compounds containing the indole framework by using a one-pot [8+2]/[5+1] cyclization sequence,[20] as is depicted in Scheme 8. Thus, chromium enynyl carbene **1g** and *N*-(4-methoxyphenyl)-8-azaheptafulvene **2b** were mixed in THF at −50°C and the solution allowed to warm to 0°C. *t*BuNC (2 equiv) was added to the resulting [8+2]-cycloadduct-containing mixture and then stirred at 70°C for 2 h to give, after solvent removal and column chromatography purification (SiO_2, hexanes/EtOAc 5:1), the cycloadduct **11** in 78% yield. In this case, the primary [8+2] cycloadduct carbene (see cycloadducts **6a**,**b** in Scheme 5 and Scheme 6) would undergo isocyanide insertion to the non-isolated metal heterocumulene species **III**, followed by metal-promoted electrocyclic ring closure to the dihydroindole adduct **10**. Upon chromatographic purification, the latter compound completely isomerizes to the aromatic dihydrocyclohepta[*b*]indole structure **11**.



Scheme 8. One-pot [8+2]/[5+1] cyclization of chromium carbene **1g**.

Because of the great significance of the indole nucleus,[21] this direct indole-ring-construction procedure was extended to the cyclic enynyl carbene complexes **1h–j** and azaheptafulvenes **2a**,**b** (Scheme 9). Following the above protocol, carbenes **1h–j** and azaheptafulvene **2a** (R^2=*p*Me-C_6H_4) were combined and the resulting mixture treated with *t*BuNC to provide an inseparable mixture of isomeric cycloheptaindoles **12** and **13** in high overall yields after chromatographic purification (Table 2, entries 1–3). On the contrary, the use of azaheptafulvene **2b** (R^2=*p*MeO-C_6H_4) resulted in the formation of a single isomer **12d** (82% yield) on reaction with **1i** (Table 2, entry 4). Furthermore, this sequence could be carried out successfully by using carbon monoxide instead of *tert*-butyl isocyanide, as the third component (Table 2, entries 5–7). Thus, after reacting carbenes **1h**,**i** and azaheptafulvenes **2a**,**b**, the flask containing the reaction



Scheme 9. [8+2]/[5+1] Cyclization process to cycloheptaindoles **12** and **13**.

(trityl tetrafluoroborate, CH_2Cl_2, 25 °C, 1 h) permitted to isolate the expected indole-fused tropylium cation **15** in 97% yield. The X-ray diffraction structure of **15** is depicted in Figure 2.[18] Therefore, both the pyrrole and the arene rings of the indole framework were built in a one-pot process by consecutive [8+2] and [5+1] cyclization steps. Notably, most general methods to synthesize the indole ring are based on the annulation of the pyrrole ring onto a pre-existing arene nucleus.[22] Moreover, the presence of the indole skeleton in innumerable natural and bioactive compounds enhances the synthetic interest in this last reaction sequence.

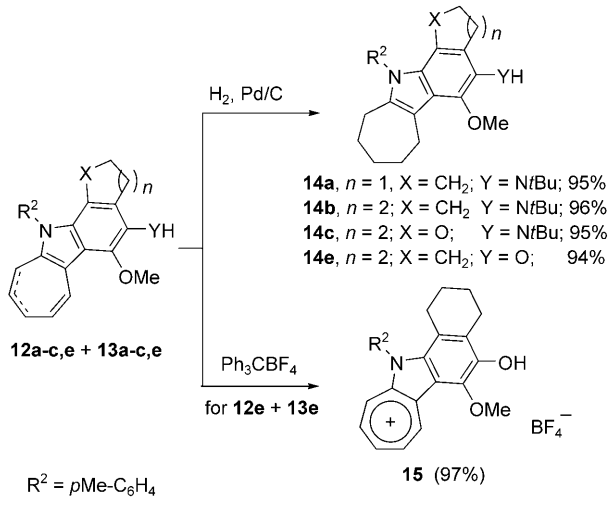
Table 2. Cycloheptaindoles **12** and **13** from carbenes **1**, azaheptafulvenes **2**, and C≡Y (CN*t*Bu/CO).

Entry	1	2	*n*	X	R^2	C≡Y	Products (**12**:**13**)	Yield [%][a]
1	**1h**	**2a**	1	CH_2	*p*Me-C_6H_4	CN*t*Bu	**12a**, **13a** (1:10)	81
2	**1i**	**2a**	2	CH_2	*p*Me-C_6H_4	CN*t*Bu	**12b**, **13b** (1:4)	89
3	**1j**	**2a**	2	O	*p*Me-C_6H_4	CN*t*Bu	**12c**, **13c** (1:2)	86
4	**1i**	**2b**	2	CH_2	*p*MeO-C_6H_4	CN*t*Bu	**12d**	82
5	**1i**	**2a**	2	CH_2	*p*Me-C_6H_4	CO	**12e**, **13e** (1:1)	75
6	**1h**	**2b**	1	CH_2	*p*MeO-C_6H_4	CO	**12f**	79
7	**1i**	**2b**	2	CH_2	*p*MeO-C_6H_4	CO	**12g**	71

[a] Overall yields after purification with column chromatography (silica gel, hexanes/EtOAc 5:1).

mixture was filled with CO (1 atm), irradiated under a UV lamp (400 W pressure mercury lamp) for 30 min, and the mixture stirred at room temperature for 12 h. Following this protocol, a 1:1 mixture of **12e** and **13e** resulted from azaheptafulvene **2a** and carbene **1i** (Table 2, entry 5), whereas single isomers **12f,g** were again exclusively isolated from azaheptafulvene **2b** and carbenes **1h,i** (Table 2, entries 6 and 7).

Furthermore, the mixtures **12a–c,e**/**13a–c,e** were hydrogenated (H_2, 1 bar, C/Pd, 25 °C, 1 h) to the single cycloheptaindoles **14a–c,e** in nearly quantitative yields (Scheme 10). Moreover, hydride extraction from the mixture of **12e**/**13e**



Scheme 10. Hydrogenation and hydride abstraction in **12** and **13**.

Conclusions

The [8+2] heterocyclization reaction of alkynyl Fischer carbenes with 8-azaheptafulvenes described herein represents an efficient and simple access to cycloheptadiene-fused pyrroles with a versatile functionality at

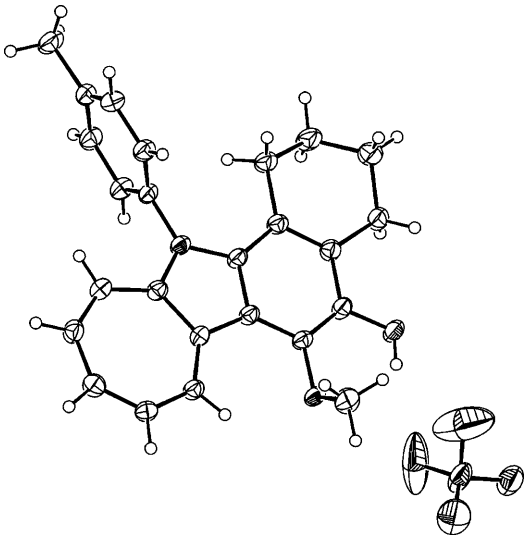


Figure 2. X-ray structure for compound **15** in the crystal. Thermal ellipsoids at the 50% probability level.

C3 (metal carbene, ester). By starting from readily available enynylcarbenes in which the alkenyl appendage is attached at the C3 position, new processes that involve consecutive cyclization reactions can be designed. Thus, the formation of the cyclopenta[*b*]pyrrole framework by the consecutive [8+2] cyclization/cyclopentannulation reactions is illustrated. More importantly, the construction of both rings of the indole skeleton is easily accomplished in a regioselective manner by the one-pot sequence that involves [8+2] cyclization/R-NC or CO insertion/ring closure. The high degree of substitution and functionalization of the resulting benzo

moiety should be noted. Finally, it is shown that pyrrole-containing cycloadducts with increasing structural complexity can be accessed if the cyclopentannulation intermediate—1,3-cyclopentadiene system—is intercepted by classic dienophiles.

Experimental Section

Typical preparation of compound 3a: A solution of alkynyl carbene **1a**[23] (168.1 mg, 0.5 mmol) and 8-*para*-tolyl-8-azaheptafulvene **2a**[24] (97.6 mg, 0.5 mmol) in THF (2 mL) was stirred under nitrogen at room temperature for 3 h. Then, the solvent was removed and the crude product purified by column chromatography (SiO_2, hexanes/EtOAc 50:1) to give **3a** (223.2 mg, 84%). ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ = 7.34–6.92 (m, 9H), 6.59–6.41 (m, 2H), 6.28–6.20 (m, 1H), 5.50–5.42 (m, 1H), 5.30–5.22 (m, 1H), 4.38 (brs, 1H), 4.14 (s, 3H), 2.31 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ =317.6 (C), 230.5 (C), 223.6 (C), 146.8 (C), 142.5 (C), 138.0 (C), 136.1 (C), 133.2 (C), 132.6 (C), 130.4 (CH), 129.3 (CH), 128.8 (CH), 128.4 (CH), 127.8 (CH), 126.3 (CH), 125.0 (CH), 114.4 (CH), 100.2 (CH), 64.1 (CH_3), 49.3 (CH), 21.0 ppm (CH_3); HRMS: *m*/*z*: calcd for $C_{29}H_{21}NO_6Cr$:. 531.0774; found: 531.0777.

Typical preparation of compound 8: Carbene **1i**[7b] (170.1 mg, 0.5 mmol) and 8-*para*-tolyl-8-azaheptafulvene **2a** (97.6 mg, 0.5 mmol) were mixed in THF (2 mL) at - 50°C and the solution allowed to slowly warm to 0°C. Then, dimethyl acetylenedicarboxilate (184 μL, 1.5 mmol) was added and the mixture warmed at 70°C for 2 h. After solvent removal, the crude mixture was purified by column chromatography (hexanes/EtOAc 3:1) to give compound **8** (150.5 mg, 62%): ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ = 7.28 (s, 4H), 6.70 (d, ^3J(H,H) = 9.5 Hz, 1H), 6.11 (d, ^3J(H,H) = 9.8 Hz, 1H), 5.39–5.31 (m, 1H), 5.22–5.13 (m, 1H), 3.82 (s, 3H), 3.75 (s, 3H), 3.61 (s, 3H), 3.31–3–26 (m, 1H), 2.87–2.72 (m, 1H), 2.46 (s, 3H), 2.32–2.24 (m, 2H), 1.81–1.72 (m, 1H), 1.69–1.58 (m, 2H), 1.54–1.43 (m, 1H), 1.38–1.34 (m, 2H), 1.20–1.16 (m, 1H), 0.93–0.87 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ = 164.8 (C), 162.0 (C), 150.2 (C), 146.7 (C), 137.7 (C), 135.2 (C), 133.1 (C), 130.4 (C), 130.0 (C), 129.4 (CH), 127.0 (CH), 122.8 (CH), 121.8 (C), 119.9 (CH), 115.5 (CH), 110.0 (CH), 97.3 (C), 85.1 (CH), 56.8 (CH_3), 55.2 (C), 52.2 (CH_3), 51.8 (CH_3), 27.2 (CH_2), 25.0 (CH_2), 24.6 (CH_2), 23.4 (CH_2), 22.8 (CH_2), 21.2 ppm (CH_3); HRMS: *m*/*z*: calcd for $C_{30}H_{31}NO_5$: 485.2197; found: 485.2199.

Typical preparation of compound 11: Enynyl carbene **1g**[7b] (168.1 mg, 0.5 mmol) and 8-*para*-methoxyphenyl-8-azaheptafulvene **2b**[24] (105.6 mg, 0.5 mmol) were mixed in THF (2 mL) under nitrogen at −50°C and the mixture allowed to slowly warm to 0°C, then *tert*-buthylisocianate (115 μL, 1 mmol) was added and the mixture warmed at 70°C for 2 h. After solvent removal, the resulting crude mixture was purified (SiO_2, hexanes/EtOAc 5:1) to give **11** (181.2 mg, 78%): ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ = 7.53–7.21 (m, 8H), 7.02 (d, ^3J(H,H) = 8.8 Hz, 2H), 6.90 (s, 1H), 6.46 (d, ^3J(H,H) = 7.2 Hz, 1H), 5.61–5.58 (m, 1H), 5.48–5.41(m, 1H), 4.11 (s, 3H), 3.85 (s, 3H), 2.61–2.47 (m, 2H), 1.03 ppm (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ = 159.8 (C), 151.1 (C), 149.1 (C), 142.5 (C), 136.7 (C), 135.4 (C), 131.3 (C), 130.5 (C), 130.1 (CH), 129.1(C), 128.9 (CH), 128.7 (CH), 128.1 (C), 126.6 (CH), 124.2 (CH), 121.4 (CH), 119.4 (CH), 114.8 (CH), 114.6 (CH), 107.4 (CH), 59.6 (CH_3), 55.5 (CH_3), 54.8 (C), 30.5 (CH_3), 27.5 ppm (CH_2); HRMS: *m*/*z*: calcd for $C_{31}H_{32}N_2O_2$: 464.2464; found: 464.2468.

Typical preparation of compound 12f: Enynyl carbene **1h**[7b] (163.1 mg, 0.5 mmol) and 8-*para*-methoxyphenyl-8-azaheptafulvene **2b** (105.6 mg, 0.5 mmol) were mixed in THF (2 mL) under nitrogen at −50°C and the mixture allowed to slowly warm to 0°C. Then, the flask was filled with CO (1 atm) and the mixture irradiated (400 W pressure mercury lamp) for 30 min and stirred for an additional 12 h at room temperature. After solvent removal, the crude product was purified (SiO_2, hexanes/EtOAc 5:1) to give **12f** (147.4 mg, 79%): ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ = 7.30 (d, ^3J(H,H) = 9.8 Hz, 1H), 7.26 (m, ^3J(H,H) = 8.7 Hz, 2H), 7.01 (d, ^3J(H,H) = 8.7 Hz, 2H), 6.27 (d, ^3J(H,H) = 9.8 Hz, 1H), 5.58–5.52 (m, 1H), 5.45(s, 1H), 5.4 (m, 1H), 3.97 (s, 3H), 3.91 (s, 3H), 2.96–2.90 (m, 2H), 2.52–2.50 (m, 2H), 2.40–2.35 (m, 2H), 2.06–1.96 ppm (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ = 159.2 (C), 139.0 (C), 138.9 (C), 137.8 (C), 131.2 (C), 130.2 (CH), 129.8 (C), 128.8 (C), 123.6 (CH), 122.4 (C), 121.1 (CH), 119.1 (CH), 118.1 (C), 115.4 (C), 114.3 (CH), 113.8 (CH), 61.3 (CH_3), 55.4 (CH_3), 31.1 (CH_2), 29.2 (CH_2), 27.3 (CH_2), 25.5 ppm (CH_2); HRMS: *m*/*z*: calcd for $C_{24}H_{23}NO_3$: 373.1678; found: 373.1670.

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