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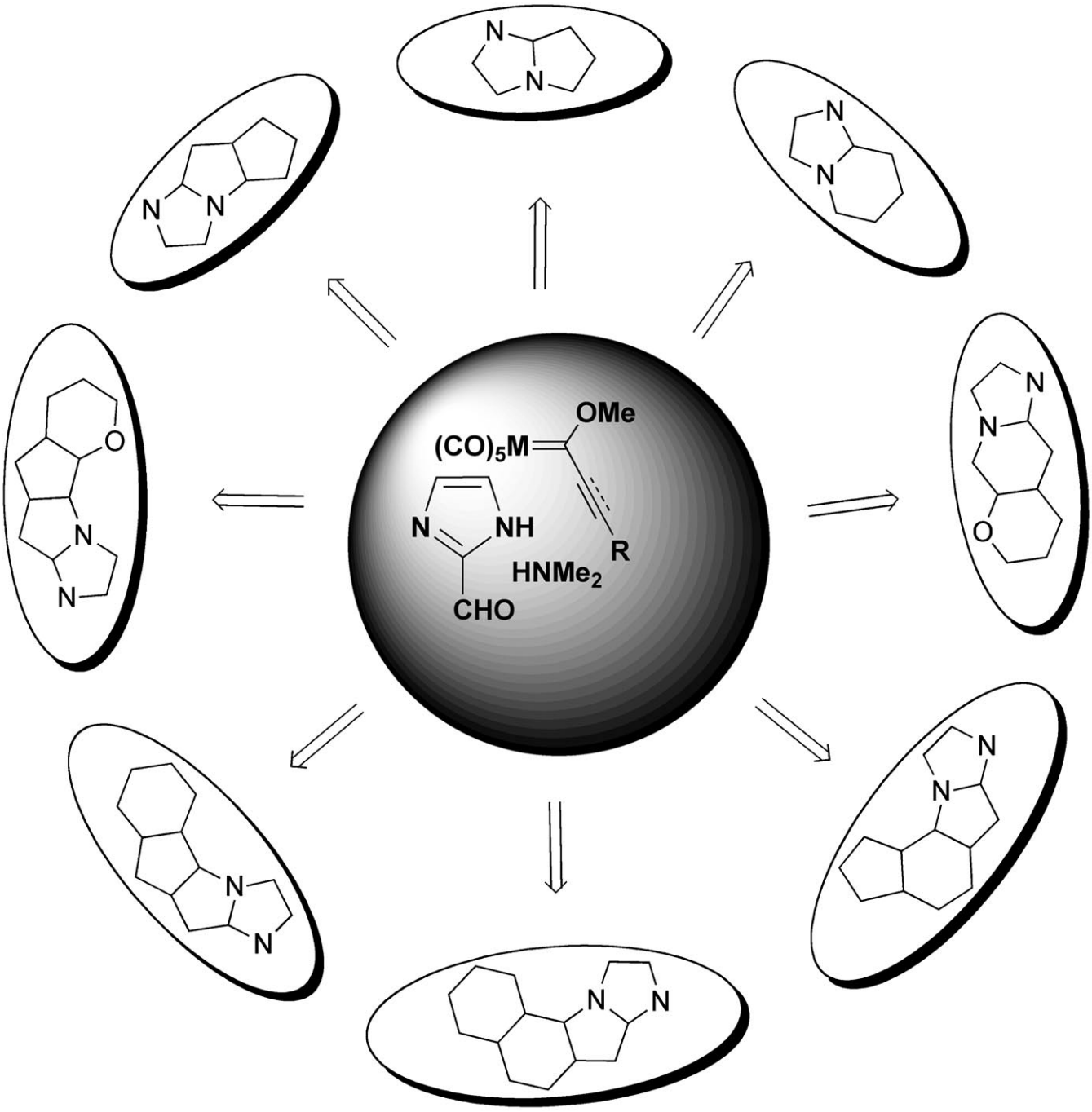

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CHEMISTRY
A EUROPEAN JOURNAL

DOI: 10.1002/chem.200501402

Facile and Versatile Annulation of the Imidazole Ring: Single and Sequential Cyclization Reactions of Fischer Carbene Complexes with 1,4-Diazafulvenes

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Abstract: We examined the reactivity of dimethylaminodiazafulvene **1** toward Fischer alkenylcarbene **2** and alkynylcarbene **3** complexes. Diazafulvene **1** reacts with alkenylcarbenes **2** through a formal [6+3] heterocyclization in a regio- and stereoselective manner to afford dihydroimidazo[1,2-*a*]pyridines **4**. Acid-promoted dimethylamine elimination in compound **4c** gives rise to the aromatic imidazo pyridine **5**. A likely mechanism for this reaction is a 1,2-nucleophilic addition/[1,2]-shift metal-promoted cyclization sequence. On the other hand, diazafulvene **1** and alkynyl carbenes **3** undergo a [6+2] cyclization to afford pyrrolo-[1,2-*a*]imidazole carbene complex **6** that can be readily oxidized to the corresponding esters **7**. When enynylcarbenes **3e–i** are treated with diazafulvene **1**, consecutive and diastereoselective [6+2]/cyclopentannulation cyclization reactions take place affording new polycyclic complex systems **8**, **9**, and **12** that can be appropriately demetallated to the corresponding imidazole-based polyfused systems **10**, **11**, and **13** respectively. Finally, enynylcarbenes **3d**,**f** undergo consecutive [6+2]/[5+1] cyclization reactions with diazafulvene **1** and *t*BuNC, respectively, to yield tetracyclic adducts **14** and **15**. All these processes result in high yields and provide a route to the preparation of imidazopyridines and pyrroloimidazoles as well as other polycyclic molecules that contain imidazole groups, which are interesting from a pharmacological and biological point of view.

Keywords: azafulvenes · carbenes · chromium · cyclization · imidazole

Introduction

Stabilized Fischer carbene complexes have been shown to be useful reagents in a number of cyclization reactions, allowing the preparation of a plethora of three- to eight-membered carbocyclic rings and acyclic compounds.[1] Despite the fact that the activated carbon–carbon double and triple bonds of α,β-unsaturated carbene complexes efficiently participate in a number of [2+2][2] and [4+2][3] cycloaddition reactions, the most characteristic and valuable reactions are those in which the metal–carbon bond is involved. Thus, a number of two-component, such as [2+1],[4] [3+1],[5] [3+2],[6] [3+3],[5,7] [4+1],[8] [4+3],[6c,8c,9] [5+1],[10] and [5+2][11] as well as multicomponent, such as [2+2+1],[12] [3+2+1],[13] [3+2+2],[14] [4+2+1],[15] [5+2+1],[16] [2+2+1+1],[12d,17] and [2+2+2+1],[14a] carbocyclization reactions have been reported in the recent past.

Despite the intensive work on carbocyclization reactions, the reactivity of metal–carbene complexes toward substrates containing heteroatoms has been much less studied. Apart from the known heterocycloaddition reactions, that is, the [4+2], [2+2], and 1,3-dipolar reactions, through the activated carbon–carbon bond of unsaturated carbene complexes,[18] the attention on heterocyclization reactions involving metal–carbene functionality has largely focused on the use of imines and unsaturated imine derivatives as substrates in both photochemical and thermal processes.[19] We have searched for new nitrogen-containing substrates and thought that diazafulvene derivatives might be appropriate candidates because we were convinced of the potential of these metal–carbene complexes as reagents in heterocyclic synthesis[20]. First, the polyvalent nature of the pentafulvene system has permitted us to selectively access different polycarbocyclic structures through [2+1], [4+3], and [6+3] cyclization reactions of Fischer carbene complexes.[21] Secondly, surprisingly few reports exist on the use of azafulvenes in heterocyclic synthesis.[22] Specifically, we thought of the 1,4-diazafulvene structure as a reactive imidazole building block

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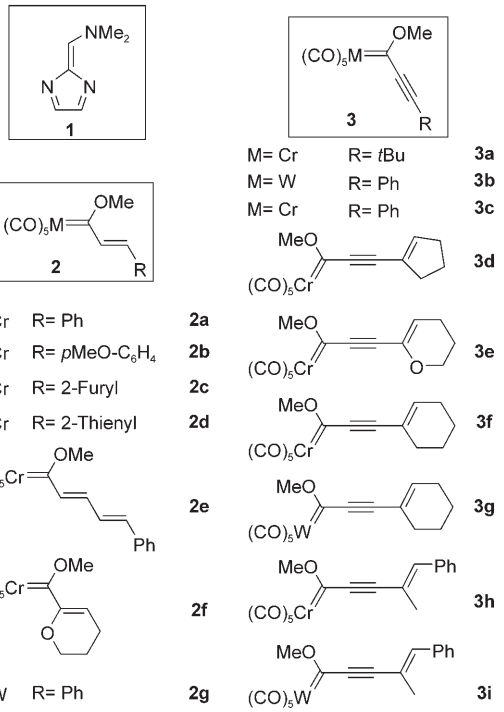
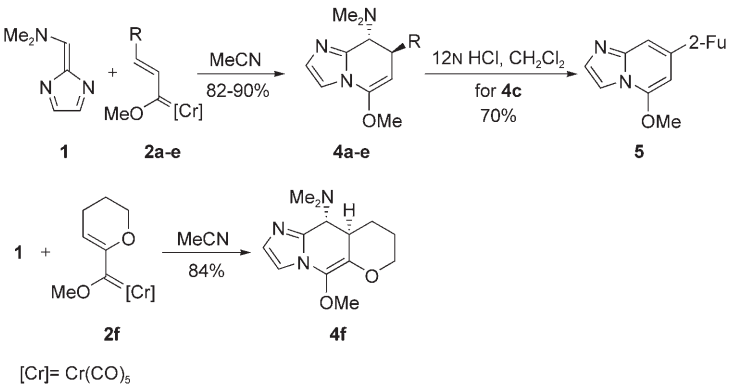
for an annulation-based strategy to rapidly prepare fused imidazole heterocycles.

Thus, we report on the reaction of the readily available 6-dimethylamino-1,4-diazafulvene (**1**)[22] with alkenyl and alkynyl Fischer carbene complexes **2** and **3** to produce simple and complex imidazo[1,2-*a*]pyridine and pyrrolo[1,2-*a*]imidazole structures, respectively.

Results and Discussion

[6+3] Cycloaddition of 6-dimethylamino-1,4-diazafulvene (1) with alkenylcarbene complexes (2): First, we examined the reactivity of alkenylcarbenes toward dimethylaminodiazafulvene (Scheme 1). Thus, chromium–alkenylcarbene complexes **2a–d** (M = Cr) were found to smoothly react with diazafulvene **1** in acetonitrile at room temperature. After stirring for one hour, the reaction mixture was subjected to demetallation (air, sunlight) and was filtered through a pad of Celite to produce nearly pure [6+3] cycloadducts **4a–d** with complete regio- and diastereoselectivity (Table 1, entries 1–4). Further column chromatography purification gave pure dihydroimidazo[1,2-*a*]pyridines **4a–d** in excellent yields (82–90%). Similarly, the dienylcarbene complex **2e** underwent cycloaddition to compound **1** in a chemoselective manner giving rise to the more-functionalized phenylethenyl derivative **4e** (R = *trans*-Ph–CH=CH) in excellent yield (Table 1, entry 5). Heterocyclic carbene complexes also work well allowing the synthesis of more complex polyheterocyclic systems. For instance, the tricyclic imidazole **4f** was obtained in 84% yield from diazafulvene **1** and chromium–carbene **2f** under the same reaction conditions (Table 1, entry 6). The tungsten–alkenylcarbene **2g** (M = W) reacted in the same way, though the resulting cycloadduct **4a** was isolated in significantly lower yield than in the case of the chromium–carbene **2a** (45 versus 82% yield; Table 1, entries 1 and 7). The *trans* relationship between the dimethylamino group and the R substituent was determined by nuclear Overhauser enhancement experiments performed on compound **4e**. The treatment of cycloadduct **4c** with concentrated HCl in dichloromethane resulted in the elimina-

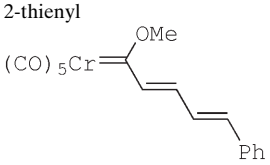
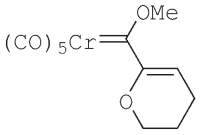




Scheme 1. [6+3] Cycloaddition of 1,4-diazafulvene **1** and alkenylcarbenes **2**.

Abstract in Spanish: *Se ha investigado la reactividad de dimetilaminodiazafulveno **1** frente a los complejos alquenilcarbeno y alquinilcarbeno de Fischer **2** y **3**. El diazafulveno **1** reacciona con los alquenilcarbenos **2** mediante una heterociclación [6+3] dando lugar a dihidroimidazo[1,2-a]piridinas **4** de forma regio- y diastereoselectiva; la eliminación de dimetilamina en medio ácido en **4c** da lugar a la imidazopiridina aromática **5**. Un mecanismo plausible para esta reacción implica una secuencia adición nucleófila-1,2/ciclación inducida por la migración-[1,2] del fragmento metálico. Por otra parte, el diazafulveno **1** y los alquinilcarbenos **3** dan lugar a una ciclación [6+2] generando los complejos carbeno con estructura de pirrolo[1,2-a]imidazol **6**, los cuales pueden oxidarse fácilmente a los correspondientes ésteres **7**. Cuando los eninilcarbenos **3e–i** reaccionan con **1** se obtienen, a través de la secuencia diastereoselectiva ciclación [6+2]/ciclopentanulación, los complejos metálicos policíclicos **8**, **9**, y **12**, cuya desmetalación en condiciones adecuadas permite acceder a los correspondientes imidazoles polifusionados **10**, **11**, y **13**, respectivamente. Finalmente, el tratamiento secuencial de los eninilcarbenos **3d,f** con diazafulveno **1** y con tBuNC da lugar a los aductos tetracíclicos **14**,**15** en un proceso multicomponente de doble ciclación [6+2] y [5+1]. Todos estos procesos tienen lugar con altos rendimientos y representan una vía de entrada a imidazopiridinas y pirroloimidazoles, así como a otras moléculas policíclicas que contienen el anillo de imidazol con interés desde el punto de vista biológico y farmacológico.*

Table 1. Dihydroimidazopyridines **4** from diazafulvene **1** and carbenes **2**.

	Carbene	R	Product	Yield [%][a]
1	**2a**	Ph	**4a**	82
2	**2b**	*p*OMe-C_6H_4	**4b**	88
3	**2c**	2-furyl	**4c**	90
4	**2d**	2-thienyl	**4d**	83
5	**2e**		**4e**	90
6	**2f**		**4f**	84
7	**2g**	Ph	**4a**	45

[a] Yields after column chromatography purification (silica gel, hexanes/EtOAc/Et_3N 8:1:1).

tion of dimethylamine and the formation of the aromatic imidazopyridine structure **5** in 70% yield. Looking at the overall process 6-dimethylamino-1,4-diazafulvene behaves as a synthon of the elusive 1,4-diazafulvene species.

A likely mechanistic rationale for this [6+3] cycloaddition reaction of alkenylcarbenes and fulvenes is based on the accepted sequence of nucleophilic addition and metal-migration-promoted cyclization (Figure 1).[23] Thus, the 1,2-addi-

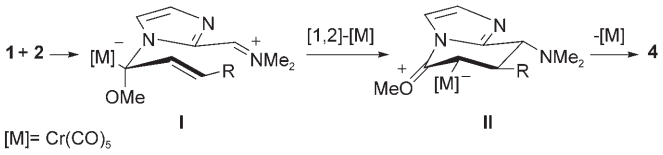
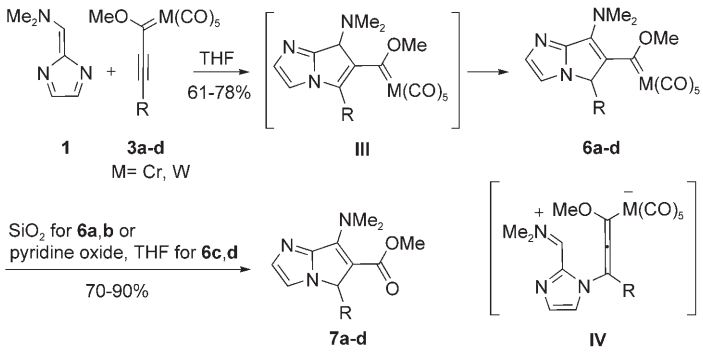


Figure 1. Feasible mechanism of the [6+3] cycloaddition of diazafulvene **1** and alkenylcarbenes **2**.

tion of the ring nitrogen atom of the diazafulvene to the carbene complex would form the intermediate **I**, which would then undergo a [1,2]-$M(CO)_5$-shift and stereoselective cyclization through the more favorable conformation to give the intermediate **II**. The last step involves metal elimination to generate the enolether functionality.

Therefore, a facile access to the imidazo[1,2-*a*]pyridine ring is accomplished by a procedure that involves annulation of the pyridine unit onto the existing imidazole ring.[24] Interestingly, most strategies leading to this heterocyclic structure are based on the construction of the imidazole ring from the pyridine nucleus and provide imidazo[1,2-*a*]pyridines substituted at the imidazole moiety.[25] Moreover, compounds of type **4** are of particular interest because many imidazo[1,2-*a*]pyridines display a broad range of pharmacological (antiinflammatory, antiviral, antibacterial, antiprotozoal, hypnotic, and anxiolytic) and biological activity (glycosidase, cyclin-dependent kinase, and H^+/K^+ ATPase enzyme inhibitors).[26,27]

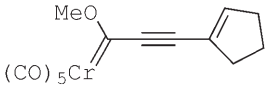
[6+2] Cycloaddition of 6-dimethylamino-1,4-diazafulvene 1 with alkynylcarbenes 3a–d: We also explored the reactivity of Fischer alkynylcarbene complexes toward 6-dimethylamino-1,4-diazafulvene (Scheme 2). Thus, it was found that the



Scheme 2. [6+2] Cyclization of diazafulvene **1** with alkynyl Fischer carbene complexes **3a–d**.

reaction of the chromium–alkynylcarbene **3a** with diazafulvene **1** went to completion after stirring in THF for one hour at room temperature. Simple column-chromatography purification of the reaction crude on silica gel yielded the new pyrrolo[1,2-*a*]imidazole–carbene complex **6a** (M = Cr; R = *t*Bu, 78%) resulting from the [6+2] cycloaddition reaction (Table 2, entry 1). The tungsten–carbene complex **3b**

Table 2. Cycloadducts **6**,**7** from diazafulvene **1** and carbenes **3a–d**.

	Carbene	M	R	Product	Yield [%][a]
1	**3a**	Cr	*t*Bu	**6a**	78
2				**7a**	88
3	**3b**	W	Ph	**6b**	61
4				**7b**	90
5	**3c**	Cr	Ph	**6c**[b]	–
6				**7b**[c]	70
7	**3d**			**6d**[b]	–
8				**7d**[c]	74

[a] Yields after column chromatography purification (silica gel, hexanes/EtOAc/Et_3N 8:1:1). [b] Carbene cycloadducts not isolated. [c] Overall yield from diazafulvene **1** and carbenes **3c**,**d**.

(M = W; R = Ph) also works well affording **6b** in 61% yield (Table 2, entry 3). Chromium–alkynyl complexes with phenyl and cyclopentenyl substituents **3c** and **3d**, respectively, undergo cycloaddition to diazafulvene **1** in the same way, though the corresponding cycloadducts **6c**,**d** could not be purified; however, they underwent oxidation to the corresponding esters **7b**,**d** in high overall yield when subjected to column chromatography (Table 2, entries 6,8). The carbene cycloadducts **6a**,**b** were in turn oxidatively demetallated to the corresponding esters **7a**,**b** (Table 2, entries 2,4). The proposed structures **6** and **7** are in good agreement with their

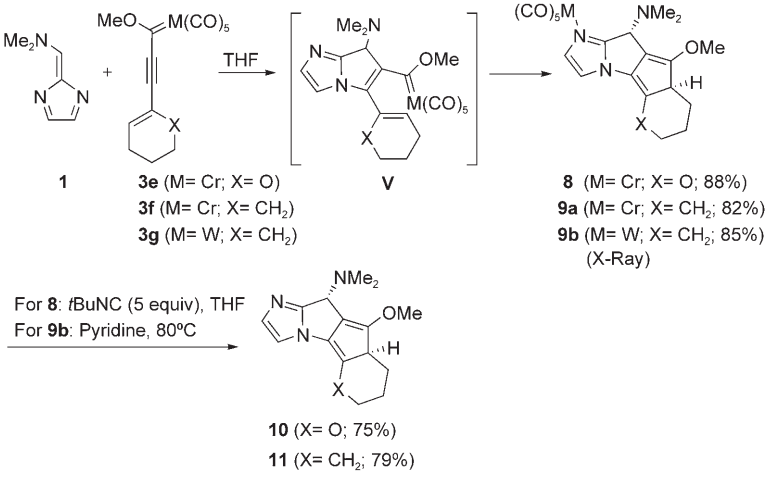
spectroscopic data. Looking at the pyrrole ring, it should be noted that the initially formed tautomer **III** isomerizes under the reaction conditions to the more stable, fully conjugated carbene system **6**. This structural feature is confirmed by HMBC (heteronuclear multiple bond correlation) and NOESY experiments on compound **7d**. The reaction can be readily understood by the conjugate nucleophilic addition of the ring nitrogen atom of diazafulvene **1** to the electrophilic alkynyl ligand **3** forming the zwitterion species **IV**,[28] which spontaneously undergoes cyclization into tautomer **III** and then isomerization into the pyrrolo[1,2-*a*]imidazole derivatives **6**.

It must be mentioned that [6+2] cycloaddition reactions of the diazafulvene system are rarely found in the literature. In an isolated case, the reaction of diazafulvene **1** with dimethyl acetylenedicarboxylate has been reported by Muchowski to occur in refluxing toluene.[22b] This fact highlights one of the advantages of carbene complexes as activated alkynes over classical metal-free electrophilic alkynes.

The occurrence of the pyrrolo[1,2-*a*]imidazole unit in several biologically active compounds, for example, several classes of pyrrolo[1,2-*a*]benzimidazole-based antitumor agents[29] increases the interest in this [6+2] cyclization reaction.

Consecutive cyclization reactions of 6-dimethylamino-1,4-diazafulvene (1) with enynylcarbene complexes 3d–i: It is known that the cyclization of conjugated *cis*-dienylcarbene(1-metalla-1,3,5-hexatriene) complexes can be promoted either thermally (pentannulation reaction)[30] or in the presence of carbon monoxide/isonitriles (benzannulation reaction).[10] In this way, one can realize that the potential of the implemented [6+2] cyclization might be significantly extended beyond a single cyclization. For instance, starting with enynylcarbenes would produce alkenyl-substituted carbene cycloadducts **6** (see Scheme 2; R = alkenyl), which seem to be appropriate candidates to produce imidazole-based polyfused systems. Unexpectedly, the dienylcarbene structure **III** (R = 1-cyclopentenyl), which is presumed to be generated upon reaction of diazafulvene **1** and carbene **3d** at room temperature (see above), does not undergo cyclization after prolonged heating at 80 °C in THF. We argued that this disappointing result might be due to stereoelectronic factors, because of the particular nature of the cyclopentenyl moiety that would slow down the cyclization and thus make the isomerization from tautomer **III** into **6d** the preferred reaction pathway (see Scheme 2).

Therefore, we turned our attention to the acyclic and cyclohexenyl analogues **3e–i** as the starting carbene complexes, for which the consecutive cyclization process would be presumably more favorable. We first explored the behavior of dihydropyranyl- and cyclohexenylethynyl carbenes **3e** and **3f**,**g**, respectively, in this process (Scheme 3). When



Scheme 3. Synthesis of tetracycles **8**–**11** from carbenes **3e**–**g** and diazafulvenes **1**.

these carbene complexes were treated with diazafulvene **1** in THF at room temperature for 1–12 h, the corresponding [6+2] cycloadducts **6e–g** were not isolated, but the tetracyclic complexes **8** and **9a**,**b** resulting from the cyclopentannulation reaction of the primary isomers **V** and the coordination of $M(CO)_5$ to the sp^2-nitrogen were obtained (82–88 % yield) with complete diastereoselectivity (Scheme 3). The relative stereochemistry of complexes **8** and **9** was determined from ^{1}H NMR nuclear Overhauser experiments and the structure of the cycloadduct **9b** was unambiguously confirmed by an X-ray analysis (Figure 2). Finally, the demetallation of complexes **8** and **9b** to give compounds **10** and **11** readily occurred by ligand displacement with *t*BuNC/THF (25 °C; 75 % yield) and pyridine (80 °C; 79 % yield), respectively. Importantly, the resulting *t*BuNC–$Cr(CO)_5$ and

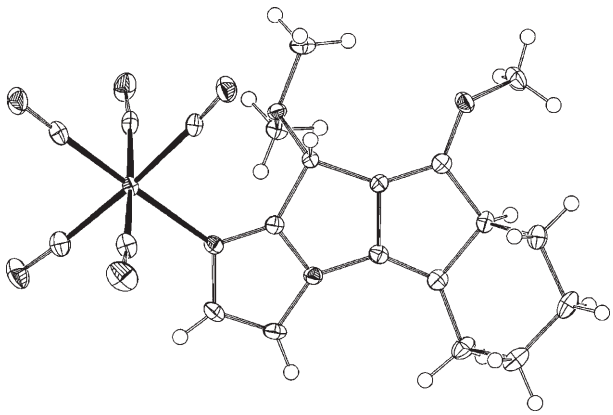
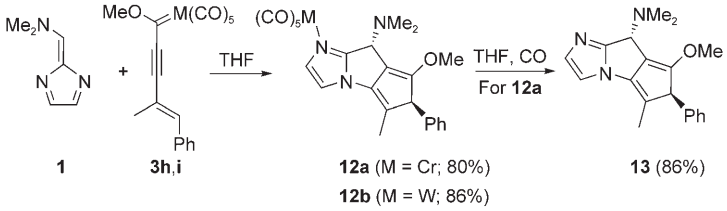


Figure 2. X-ray crystal structure of compound **9b**.

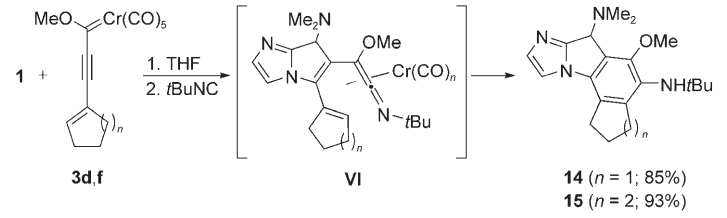
pyridine–$W(CO)_5$ complexes could be quantitatively recovered.

The acyclic enynylcarbene complexes **3h**,**i** were found to behave similarly toward the diazafulvene **1**. Thus, the consecutive [6+2] cyclization/pentannulation reaction takes place in THF at room temperature to produce the tricyclic adducts **12a**,**b** in 80–85% yield (Scheme 4) regio- and stereoselectively. The structure and the relative stereochemistry of adducts **12** was confirmed by HMBC and NOESY experiments conducted on compound **12b**. The metal decoordination to the metal-free cycloadduct **13** was accomplished in 86% yield by bubbling CO gas into a solution of compound **12a** in THF.



Scheme 4. Tricycles **12** and **13** from reaction of diazafulvene **1** and carbenes **3h**,**i**.

The usefulness of the cyclization process to synthesize complex heteropolycyclic targets could be further enhanced by using the one-pot [6+2] cyclization/[5+1] cyclization sequence, as outlined in Scheme 5. Thus, cyclopentenyl- and



Scheme 5. [6+2] Cyclization/isocyanide insertion of Fischer carbenes **3d**,**f**.

cyclohexenylethenylcarbene complexes of chromium **3d** and **3f** were stirred with diazafulvene **1** at room temperature in THF for one hour with the expectation that the corresponding [6+2] cycloadducts of type **V** had been formed. Then, *t*BuNC (2 equiv) was added and the mixture stirred for one additional hour to give, after column chromatography purification (SiO_2, hexanes/ethyl acetate 5:1), the cycloadducts **14** ($n=1$) and **15** ($n=2$) in high yields (85–93%). In these cases, the primary [6+2] cycloadducts would undergo isocyanide insertion to produce the nonisolated metal heterocumulene species **VI**[31] followed by metal-promoted electrocyclic ring-closure and isomerization to the aromatic ring.

Conclusion

A new set of heterocyclization reactions of Group 6 Fischer carbene complexes toward 6-dimethylamino-1,4-diazafulvene have been performed. Alkenylcarbene complexes provide high yields of imidazo[1,2-*a*]pyridines with complete regio- and stereoselectivity through a [6+3] heterocyclization. On the other hand, the first [6+2] cyclization of alkynylcarbene complexes was found to occur upon reaction with the diazafulvene system affording pyrrolo[1,2-*a*]imidazole derivatives. The presence of the metal–carbene functionality for the latter allows cascade heteropolycyclization reactions to occur, for example, [6+2] cyclization/pentannulation and [6+2] cyclization/[5+1] cyclization. From a synthesis point of view, a new strategy based on Fischer carbene complexes has been implemented for the rapid preparation of simple bicyclic imidazole systems, like imidazopyridines and pyrroloimidazoles, as well as rarer complex derivatives, such as tricyclic and tetracyclic imidazole-containing molecules. It is also worth noting the ready availability of the starting materials on the multigram scale as well as the ease with which the experimental synthesis is executed. Finally, an additional point of interest is that the biological activity of fused imidazoles, or molecules containing that unit, is currently well-documented.

Experimental Section

General: All reactions involving air-sensitive compounds were carried out under nitrogen atmosphere (99.99%). All glassware was oven-dried (120°C), evacuated, and purged with nitrogen. All common reagents and solvents were obtained from commercial suppliers and used without any further purification unless otherwise indicated. Fischer carbene complexes **2**,**3**[2i,3f,32] and the diazafulvene **1**[22] were prepared by following the described procedures. Solvents were dried by standard methods and distilled prior to use. Flash column chromatography was carried out on silica gel 60, 230–240 mesh. NMR measurements were recorded on Bruker AC-200, AC-300, or DPX-300 spectrometers. ^{1}H NMR spectra were recorded in $CDCl_3$ (unless otherwise noted) at 300.08 MHz at 20°C with tetramethylsilane ($\delta=0.0$ ppm) as the internal standard. ^{13}C NMR spectra were recorded in $CDCl_3$ (unless otherwise noted) at 75.46 MHz at 20°C. ^{1}H NMR splitting pattern abbreviations are: s, singlet; d, doublet; m, multiplet. ^{13}C NMR multiplicities were determined by DEPT, abbreviations are: q, CH_3; t, CH_2; d, CH; s, quaternary carbon atoms, some ^{13}C NMR signals overlap. COSY, HMSQC, HMBC, and NOESY experiments were carried out on a Bruker AMX-400 spectrometer. Standard pulse sequences were employed for the DEPT experiments. High-resolution mass spectra (HRMS) were obtained with a Finnigan Mat 95 mass spectrometer and electron impact techniques (70 eV) were employed. Elemental analyses were carried out with a Perkin–Elmer 240 B microanalyzer.

General procedure for synthesis of dihydroimidazo[1,2-*a*]pyridines (4): A solution of diazafulvene **1** (0.75 mmol) and carbenes **2** (0.5 mmol) in MeCN (3 mL) was stirred under nitrogen at room temperature for 1 h. Then, the solvent was removed in vacuo and the crude product dissolved in a mixture of EtOAc/hexane (1:1) and oxidized by air in an open flask in sunlight (10–12 h). The solution was then filtered through Celite, and the filtrate was concentrated under vacuum. The resulting crude product was purified by column chromatography (silica gel, hexanes/EtOAc/Et_3N 8:1:1).

[(7*S*,8*S*)/(7*R*,8*R*)-5-Methoxy-7-phenyl-7,8-dihydroimidazo[1,2-*a*]pyridin-8-yl]dimethylamine (4a): Yield = 82%; ^{1}H NMR: δ = 7.2 (s, 1H), 7.1–7.2 (m, 3H), 7.0 (s, 1H), 6.9 (m, 2H), 4.5 (d, J = 5.9 Hz, 1H), 3.9 (d, J = 5.9 Hz, 1H), 3.8 (s, 1H), 3.7 (s, 3H), 2.3 ppm (s, 6H); ^{13}C NMR: δ = 145.6 (s), 142.4 (s), 141.0 (s), 128.1 (d), 127.3 (d), 126.2 (d), 112.4 (d), 82.0 (d), 63.1 (q), 54.8 (d), 42.7 (d), 41.5 ppm (q); HRMS: m/z: calcd for $C_{16}H_{19}N_3O$: 269.1522; found: 269.1512 $[M]^+$; elemental analysis calcd (%) for $C_{16}H_{19}N_3O$: C 71.35, H 7.11, N 15.60; found: C 71.18, H 7.22, N 15.52.

[(7*S*,8*S*)/(7*R*,8*R*)-5-Methoxy-7-(4-methoxyphenyl)-7,8-dihydroimidazo-[1,2-*a*]pyridin-8-yl]dimethylamine (4b): Yield = 88%; ^{1}H NMR: δ = 7.2 (s, 1H), 7.0 (s, 1H), 6.9 (d, J = 8.5 Hz, 2H), 6.7 (d, J = 8.5 Hz, 2H), 4.5 (d, J = 5.8 Hz, 1H), 3.9 (d, J = 5.8 Hz, 1H), 3.85 (s, 1H), 3.7 (s, 3H), 3.6 (s, 3H), 2.3 ppm (s, 6H); ^{13}C NMR: δ = 158.0 (s), 145.7 (s), 141.4 (s), 134.7 (s), 127.7 (d), 127.5 (d), 113.6 (d), 112.5 (d), 82.5 (d), 63.6 (d), 55.0 (q), 54.7 (q), 42.1 (d), 41.8 ppm (q); HRMS: m/z: calcd for $C_{17}H_{21}N_3O_2$: 299.1628; found: 299.1633 $[M]^+$.

[(7*S*,8*S*)/(7*R*,8*R*)-7-(Furan-2-yl)-5-methoxy-7,8-dihydroimidazo[1,2-*a*]pyridin-8-yl]dimethylamine (4c): Yield = 90%; ^{1}H NMR: δ = 7.3 (s, 1H), 7.2 (s, 1H), 7.0 (m, 1H), 6.2 (m, 1H), 5.9 (m, 1H), 4.5 (d, J = 6.7 Hz, 1H), 4.0 (s, 1H), 3.95 (d, J = 6.7 Hz, 1H), 3.8 (s, 3H), 2.3 ppm (s, 6H); ^{13}C NMR: δ = 154.8 (s), 146.6 (s), 142.0 (s), 141.6 (d), 127.8 (d), 112.9 (d), 109.9 (d), 105.2 (d), 79.2 (d), 60.8 (d), 55.3 (q), 42.1 (q, 2C), 36.5 ppm (d); HRMS: m/z: calcd for $C_{14}H_{17}N_3O_2$: 259.1315; found: 259.1315 $[M]^+$; elemental analysis calcd (%) for $C_{14}H_{17}N_3O_2$: C 64.85, H 6.61, N 16.20; found: C 64.92, H 6.80, N 16.29.

[(7*S*,8*S*)/(7*R*,8*R*)-5-Methoxy-7-(thiophen-2-yl)-7,8-dihydroimidazo[1,2-*a*]pyridin-8-yl]dimethylamine (4d): Yield = 83%; ^{1}H NMR: δ = 7.2 (s, 1H), 7.0–7.1 (m, 2H), 6.8 (m, 1H), 6.7 (m, 1H), 4.6 (d, J = 6.1 Hz, 1H), 4.2 (d, J = 6.1 Hz, 1H), 3.9 (s, 1H), 3.8 (s, 3H), 2.3 ppm (s, 6H); ^{13}C NMR: δ = 147.6 (s), 147.1 (s), 142.5 (s), 129.0 (d), 127.6 (d), 124.6 (d), 124.4 (d), 113.8 (d), 83.4 (d), 65.4 (d), 56.3 (q), 43.2 (q), 39.1 ppm (d); HRMS: m/z: calcd for $C_{14}H_{17}N_3OS$: 275.1086; found: 275.1087 $[M]^+$.

[(7*S*,8*S*)/(7*R*,8*R*)-5-Methoxy-7-styryl-7,8-dihydroimidazo[1,2-*a*]pyridin-8-yl]dimethylamine (4e): Yield = 90%; ^{1}H NMR: δ = 7.2–7.3 (m, 6H), 7.0 (s, 1H), 6.4 (d, J = 15.6 Hz, 1H), 5.9 (dd, J = 15.6, 7.9 Hz, 1H), 4.5 (d, J = 6.2 Hz 1H), 3.8 (s, 3H), 3.7 (s, 1H), 3.5 (dd, J = 7.9, 6.2 Hz, 1H), 2.3 ppm (s, 6H); ^{13}C NMR: δ = 145.9 (s), 142.0 (s), 136.8 (s), 129.8 (d), 128.4 (d), 127.8 (d), 127.3 (d), 126.2 (d), 113.1 (d), 81.0 (d), 61.8 (d), 55.4 (q), 42.3 (q), 40.7 ppm (d); HRMS: m/z: calcd for $C_{18}H_{21}N_3O$: 295.1679; found: 295.1673 $[M]^+$; elemental analysis calcd (%) for $C_{18}H_{21}N_3O$: C 73.19, H 7.17, N 14.23; found: C 73.03, H 7.21, N 14.01.

[(9a*S*,10*S*)/(9a*R*,10*R*)-5-Methoxy-7,8,9,9*a*-tetrahydro-10*H*-pyrano[3′,2′-*d*]imidazo[1,2-*a*]pyridin-10-yl]dimethylamine (4f): Yield = 84%; ^{1}H NMR (C_6D_6): δ = 7.3 (d, J = 1.2 Hz, 1H), 7.1 (d, J = 1.2 Hz, 1H), 3.9 (m, 1H), 3.7 (s, 3H), 3.5 (d, J = 10.6 Hz, 1H), 3.2 (m, 1H), 2.7 (s, 6H), 2.6 (m, 1H), 2.2 (m, 1H), 1.5 (m, 1H), 1.2 (m, 1H), 1.0 ppm (m, 1H); ^{13}C NMR (C_6D_6): δ = 141.8 (s), 134.0 (s), 129.3 (d), 113.2 (d), 70.0 (t), 65.1 (q), 61.3 (d), 42.3 (q), 38.2 (d), 30.1 (t), 26.1 ppm (t); HRMS: m/z: calcd for $C_{13}H_{19}N_3O_2$: 249.1471; found: 249.1468 $[M]^+$; elemental analysis calcd (%) for $C_{13}H_{19}N_3O_2$: C 62.63, H 7.68, N 16.85; found: C 62.45, H 7.75, N 16.72.

Synthesis of imidazo[1,2-*a*]pyridine 5: A solution of compound **4c** (130 mg, 0.5 mmol) in CH_2Cl_2 (3 mL) was treated with HCl (12 N, 1 mL) and the mixture stirred for 3 h. After extraction, workup, and solvent removal, the resulting crude was purified by column chromatography (silica gel, hexanes/EtOAc/Et_3N 8:1:1) to afford pure compound **5** (75.0 mg, 70%); ^{1}H NMR: δ = 7.65 (m, 2H), 7.6 (s, 1H), 7.5 (s, 1H), 6.7 (m, 1H), 6.5 (m, 1H), 6.4 (s, 1H), 4.1 ppm (s, 3H); ^{13}C NMR: δ = 152.3 (s), 149.5 (s), 142.7 (d), 135.6 (d), 128.4 (s), 111.9 (d), 108.0 (d), 106.7 (d), 103.7 (d), 84.5 (d), 56.3 ppm (q); HRMS: m/z: calcd for $C_{12}H_{10}N_2O_2$: 214.0736; found: 214.0730 $[M]^+$; elemental analysis calcd (%) for $C_{12}H_{10}N_2O_2$: C 67.28, H 4.71, N 13.08; found: C 67.21, H 4.78, N 12.94.

Synthesis of pyrrolo[1,2-*a*]imidazole compounds 6 and 7: A solution of carbene complexes **3** (0.5 mmol) and diazafulvene **1** (0.5 mmol) in THF (5 mL) was stirred at room temperature for 1 h. Then, the solvent was removed and the resulting crude was purified by column chromatography (silica gel, hexanes/EtOAc/Et_3N 8:1:1).

Adducts **6a** and **6b** were oxidized to the corresponding esters **7a** and **7b** by treatment in THF with 3 equiv of pyridine oxide followed by extraction, workup, and purification as above.

Chromium–carbene 6a: Yield = 78%; ^{1}H NMR: δ = 7.1 (s, 1H), 7.0 (s, 1H), 5.1 (s, 1H), 4.8 (s, 3H), 2.2 (s, 6H), 1.3 ppm (s, 9H); ^{13}C NMR: δ = 351.7 (s), 222.6 (s), 215.6 (s), 151.3 (s), 140.7 (s), 140.4 (s), 135.8 (d), 114.1 (d), 67.7 (d), 66.9 (q), 40.0 (q), 33.6 (s), 29.0 ppm (q); HRMS: m/z: calcd for $C_{19}H_{21}CrN_3O_6$: 439.0830; found: 439.0839 $[M]^+$; elemental analysis calcd (%) for $C_{19}H_{21}CrN_3O_6$: C 51.94, H 4.82, N 9.56; found: C 51.74, H 4.80, N 9.70.

Tungsten–carbene 6b: Yield = 61%; ^{1}H NMR: δ = 7.3–7.4 (m, 5H), 7.3 (s, 1H), 7.1 (s, 1H), 6.5 (s, 1H), 4.4 (s, 3H), 3.6 ppm (s, 6H); ^{13}C NMR: δ = 264.4 (s), 202.0 (s), 199.4 (s), 150.3 (s), 147.2 (s), 140.2 (s), 136.8 (d), 130.1 (s), 129.8 (d), 129.5 (d), 127.8 (d), 117.7 (d), 67.7 (d), 65.8 (q), 46.1 ppm (q); HRMS: m/z: calcd for $C_{21}H_{17}N_3O_6W$: 591.0621; found: 591.0629 $[M]^+$; elemental analysis calcd (%) for $C_{21}H_{17}N_3O_6W$: C 42.66, H 2.90, N 7.11; found: C 42.85, H 2.99, N 7.29.

Compound 7a: Yield = 88%; ^{1}H NMR: δ = 7.2 (s, 1H), 7.1 (s, 1H), 4.7 (s, 1H), 3.7 (s, 3H), 3.5 (s, 6H), 0.8 ppm (s, 9H); ^{13}C NMR: δ = 164.3 (s), 151.7 (s), 151.2 (s), 133.1 (d), 118.1 (d), 98.4 (s), 69.5 (d), 50.1 (q), 44.1 (q), 29.6 (s), 26.30 ppm (q); HRMS: m/z: calcd for $C_{14}H_{21}N_3O_2$: 263.1634; found: 263.1627 $[M]^+$.

Compound 7b: Yield = 70%; ^{1}H NMR: δ = 7.3 (m, 4H), 7.1 (m, 2H), 6.8 (s, 1H), 5.7 (s, 1H), 3.55 (s, 3H), 3.5 ppm (s, 6H); ^{13}C NMR: δ = 163.8 (s), 150.5 (s), 148.3 (s), 139.9 (s), 134.2 (d), 128.5 (d), 128.0 (d), 127.0 (d), 115.8 (d), 101.7(s), 63.1 (d), 50.3 (q), 43.5 ppm (q); HRMS: m/z: calcd for $C_{16}H_{17}N_3O_2$ 283.1321; found: 283.1329 $[M]^+$; elemental analysis calcd (%) for $C_{16}H_{17}N_3O_2$: C 67.83, H 6.05, N 14.83; found: C 67.97, H 5.89, N 14.98.

Compound 7d: Yield = 74%; ^{1}H NMR: δ = 7.2 (s, 1H), 6.9 (s, 1H), 5.7 (s, 1H), 5.3 (s, 1H), 3.6 (s, 3H), 3.3 (s, 6H), 2.3 (m, 2H), 1.9 (m, 1H), 1.7 (m, 2H), 1.5 ppm (m, 1H); ^{13}C NMR: δ = 164.6 (s), 151.0 (s), 148.9 (s), 142.0 (s), 134.0 (d), 130.7 (d), 116.4 (d), 99.8 (s), 60.4 (d), 50.9 (q), 44.0 (q), 32.9 (t), 29.6 (t), 23.3 ppm (t); HRMS: m/z: calcd for $C_{15}H_{19}N_3O_2$: 273.1477; found: 273.1473 $[M]^+$; elemental analysis calcd (%) for $C_{15}H_{19}N_3O_2$: C 65.91, H 7.01, N 15.37; found: C 65.78, H 7.08, N 15.23.

Preparation of polycyclic complexes 8, 9, and 12: Carbenes **3e–i** (0.5 mmol) and diazafulvene **1** (0.5 mmol) were dissolved in THF (3 mL) and the solution stirred for 12 h (1 h for compound **3e**). After solvent removal the crude was purified by column chromatography (silica gel, hexanes/EtOAc 5:1).

Chromium complex 8: Yield = 88%; ^{1}H NMR: δ = 7.2 (s, 1H), 7.0 (s, 1H), 4.9 (s, 1H), 4.3 (m, 1H), 3.8 (s, 3H), 3.7 (m, 1H), 3.4 (dd, J = 12.5, 6.2 Hz, 1H), 2.5 (m, 1H), 2.2 (s, 6H), 1.8–2.0 (m, 2H), 1.6 ppm (m, 1H); ^{13}C NMR: δ = 221.1 (s), 214.9 (s), 158.8 (s), 153.8 (s), 138.0 (d), 127.2 (s), 114.1 (s), 113.3 (d), 111.9 (s), 72.1 (t), 60.4 (d), 58.9 (q), 47.5 (d), 40.9 (q), 26.8 (t), 24.8 ppm (t); HRMS: m/z: calcd for $C_{20}H_{19}CrN_3O_7$: 465.0628; found: 465.0633 $[M]^+$; elemental analysis calcd (%) for $C_{20}H_{19}CrN_3O_7$: C 51.62, H 4.12, N 9.03; found: C 51.83, H 4.23, N 8.94.

Chromium complex 9a: Yield = 82%; ^{1}H NMR: δ = 7.1 (s, 1H), 7.0 (s, 1H), 4.9 (s, 1H), 3.9 (s, 3H), 3.4 (m, 1H), 2.7 (m 1H), 2.5 (m, 1H), 2.4 (s, 6H), 1.9 (m, 2H), 1.4 (m, 1H), 1.2 (m, 2H), 0.9 ppm (m, 1H); ^{13}C NMR: δ = 221.2 (s), 214.9 (s), 161.4 (s), 160.1 (s), 138.2 (d), 129.6 (s), 112.6 (d), 112.1 (s), 109.9 (s), 60.3 (d), 58.9 (q), 52.8 (d), 41.0 (q), 31.2 (t), 27.6 (t), 25.1 (t), 24.8 ppm (t); HRMS: m/z: calcd for $C_{21}H_{21}CrN_3O_6$: 463.0830; found: 463.0830 $[M]^+$.

Tungsten complex 9b: Yield = 85%; ^{1}H NMR: δ = 7.2 (s, 1H), 7.1 (s, 1H), 4.8 (s, 1H), 4.1 (s, 3H), 3.1 (dd, J = 12.3, 5.7 Hz, 1H), 2.7 (m 1H), 2.35 (m, 1H), 2.3 (s, 6H), 2.1 (m, 1H), 1.7–1.9 (m, 2H), 1.4 (m, 1H), 1.0–1.3 ppm (m, 2H); ^{13}C NMR: δ = 203.9 (s), 199.6 (s), 162.7 (s), 161.0 (s), 140.5 (d), 130.5 (s), 114.2 (d), 112.7 (s), 111.6 (s), 61.7 (d), 60.0 (q), 53.9 (d), 42.1 (q), 32.2 (t), 28.7 (t), 26.2 (t), 25.8 ppm (t); HRMS: m/z: calcd for $C_{21}H_{21}N_3O_6W$: 595.0934; found: 595.0918 $[M]^+$; elemental analysis calcd (%) for $C_{21}H_{21}N_3O_6W$: C 42.37, H 3.56, N 7.06; found: C 42.20, H 3.71, N 6.92.

Chromium complex 12a: Yield = 80%; ^{1}H NMR: δ = 7.5–7.2 (m, 5H), 7.1 (s, 1H), 7.0 (s, 1H), 5.0 (s, 1H), 4.6 (s, 1H), 3.6 (s, 3H), 2.3 (s, 6H),

1.7 ppm (s, 3H); ^{13}C NMR: δ=221.2 (s), 214.9 (s), 160.1 (s), 160.0 (s), 138.6 (d), 135.9 (s), 133.8 (s), 129.1 (d), 127.8 (d), 127.5 (d), 113.2 (s), 112,6 (d), 107.9 (s), 62.2 (d), 60.6 (d), 58.7 (q), 41.1 (q), 10.8 ppm (q); HRMS: *m*/*z*: calcd for $C_{24}H_{21}CrN_3O_6$: 499.0835; found: 499.0839 $[M]^+$.

Tungsten complex 12b: Yield=86%; ^{1}H NMR (C_6D_6): δ=7.3–7.1 (m, 3H), 7.0 (d, J=6.6 Hz, 2H), 6.9 (s, 1H), 6.4 (s, 1H), 4.9 (s, 1H), 4.1 (s, 1H), 3.1 (s, 3H), 2.2 (s, 6H), 1.5 ppm (s, 3H); ^{13}C NMR (C_6D_6): δ=202.5 (s), 199.1 (s), 160.2 (s), 159.5 (s), 139.7 (d), 136.7 (s), 133.6 (s), 129.1 (d), 127.9 (d), 127.7 (d), 112.9 (d), 112.5 (s), 108.0 (s), 62.0 (d), 61.1 (d), 58.1 (q), 40.9 (q), 10.2 ppm (q); HRMS: *m*/*z*: calcd for $C_{24}H_{21}N_3O_6W$: 631.0940; found: 631.0953 $[M]^+$; elemental analysis calcd (%) for $C_{24}H_{21}N_3O_6W$: C 45.66, H 3.35, N 6.66; found: C 45.70, H 3.38, N 6.79.

Demetallation of complex 8 to give compound 10: *t*BuNC (1.5 mmol) was added to a solution containing complex **8** (140 mg, 0.3 mmol) in THF (3 mL) and the mixture was stirred for 12 h. After solvent removal the crude was purified by column chromatography (silica gel, hexanes/EtOAc/Et_3N 8:1:1) to afford of compound **10** (62 mg, 75%); ^{1}H NMR (C_6D_6): δ=7.3 (s, 1H), 7.2 (s, 1H), 4.8 (s, 1H), 3.9 (s, 3H), 3.4 (m, 2H), 3.1 (m, 1H), 2.4 (s, 6H), 2.2 (m, 1H), 1.5–1.4 (m, 2H), 1.2 ppm (s, 1H); ^{13}C NMR (C_6D_6): δ=156.5 (s), 154.5 (s), 133.6 (d), 124.8 (s), 115.8 (s), 112.8 (d), 110.7 (s), 71.9 (t), 60.4 (d), 58.3 (q), 48.8 (d), 40.9 (q), 27.1 (t), 25.3 ppm (t); HRMS: *m*/*z*: calcd for $C_{15}H_{19}N_3O_2$: 273.1477; found: 273.1468 $[M]^+$; elemental analysis calcd (%) for $C_{15}H_{19}N_3O_2$: C 65.91, H 7.01, N 15.37; found: C 66.10, H 7.09, N 15.49.

Demetallation of complex 9b to give compound 11: Compound **9b** (180 mg, 0.3 mmol) was dissolved in pyridine (3 mL) and the solution heated at 80°C for 3 h. Then the solvent was removed and the crude purified by column chromatography (silica gel, hexanes/EtOAc/Et_3N 8:1:1) to yield of compound **11** (64 mg, 79%); ^{1}H NMR: δ=7.1 (d, J=1.4 Hz, 1H), 7.15 (d, J=1.4 Hz, 1H), 4.8 (s, 1H), 4.0 (s, 3H), 3.1 (dd, J=12.2, 5.4 Hz, 1H), 2.7–2.6(m, 2H), 2.3 (s, 6H), 2.2 (m, 1H), 2.0–1.9 (m, 2H), 1.4 (m, 1H), 1.2–1.1 ppm (m, 2H); ^{13}C NMR: δ=161.6 (s), 157.3 (s), 132.7 (d), 130.9 (s), 112.0 (d), 110.8 (s), 106.4 (s), 59.9 (d), 58.8 (q), 53.8 (d), 40.7 (q), 30.9 (t), 29.6 (t), 27.9 (t), 24.9 ppm (t); HRMS: *m*/*z*: calcd for $C_{16}H_{21}N_3O$: 271.1679; found: 271.1681 $[M]^+$; elemental analysis calcd (%) for $C_{16}H_{21}N_3O$: C 70.82, H 7.80, N 15.49; found: C 70.75, H 7.92, N 15.37.

Demetallation of complex 12a to give compound 13: Compound **12a** (150 mg, 0.3 mmol) was dissolved in THF (2 mL) and CO gas was bubbled through the solution for 1 h. The mixture was filtered through Celite and the filtrate was concentrated in vacuo. The resulting crude was purified by column chromatography (silica gel, hexanes/EtOAc/Et_3N 8:1:1) to yield compound **13** (80 mg, 86%); ^{1}H NMR: δ=7.3 (m, 3H), 7.25 (s, 1H), 7.2 (s, 1H), 7.1 (d, J=6.6 Hz, 2H), 5.0 (s, 1H), 4.4 (s, 1H), 4.0 (s, 3H), 2.4 (s, 6H), 1.7 ppm (s, 3H); ^{13}C NMR: δ=160.7 (s), 157.1 (s), 137.8 (s), 133.5 (d), 130.9 (s), 129.2 (d), 128.6 (d), 127.6 (d), 112.5 (d), 112.3 (s), 104.6 (s), 63.8 (d), 60.6 (d), 59.5 (q), 41.2 (q), 11.2 ppm (q); HRMS: *m*/*z*: calcd for $C_{19}H_{21}N_3O$: 307.1685; found: 307.1681 $[M]^+$; elemental analysis calcd (%) for $C_{19}H_{21}N_3O$: C 74.24, H 6.89, N 13.67; found: C 74.13, H 6.77, N 13.60.

Synthesis of tetracycles 14 and 15: A solution of carbenes **3d**,**f** (0.5 mmol) and diazafulvene **1** (0.5 mmol) in THF (3 mL) was stirred for 1 h, then *t*BuNC (1 mmol) was added and the mixture stirred further for 1 h. After solvent removal the resulting crude was purified by column chromatography (silica gel, hexanes/EtOAc 5:1).

Compound 14: Yield=85%; ^{1}H NMR: δ=7.2 (s, 1H), 7.1 (s, 1H), 5.0 (s, 1H), 3.8 (s, 3H), 3.1 (m, 2H), 2.9 (m, 2H), 2.3 (s, 6H), 2.2 (m, 2H), 1.2 ppm (s, 9H); ^{13}C NMR: δ=152.7 (s), 151.8 (s), 143.6 (s), 132.5 (d), 132.3 (s), 130.4 (s), 121.4 (s), 121.2 (s), 111.7 (d), 62.5 (d), 58.7 (q), 55.3 (s), 40.7 (q), 33.1 (t), 30.5 (q), 29.9 (t), 26.3 ppm (t); HRMS: *m*/*z*: calcd for $C_{20}H_{28}N_4O$: 340.2258; found: 340.2259 $[M]^+$; elemental analysis calcd (%) for $C_{20}H_{28}N_4O$: C 70.56, H 8.29, N 16.46; found: C 70.44, H 8.27, N 16.59.

Compound 15: Yield=93%; ^{1}H NMR: δ=7.4 (d, J=1.3 Hz, 1H), 7.1 (d, J=1.3 Hz, 1H), 4.9 (s, 1H), 4.0 (s, 3H), 2.9 (m, 2H), 2.7 (m, 2H), 2.3 (s, 6H), 1.9–1.7 (m, 4H), 1.2 ppm (s, 9H); ^{13}C NMR: δ=153.4 (s), 151.8(s), 137.0 (s), 135.3 (s), 134.0 (s), 132.7 (d), 121.4 (s), 116.7 (s), 114.2 (d), 62.5 (d), 59.0 (q), 55.3 (s), 41.2 (q), 31.3 (q), 28.4 (t), 25.7 (t), 23.1 (t), 22.8 ppm (t); HRMS: *m*/*z*: calcd for $C_{21}H_{30}N_4O$: 354.2414; found: 354.2418 $[M]^+$; elemental analysis calcd (%) for $C_{21}H_{30}N_4O$: C 71.15, H 8.53, N 15.80; found: C 71.23, H 8.76, N 15.87.

X-ray crystal structure determination: The most relevant crystal and refinement data for **9b** are as follows: empirical formula $C_{21}H_{21}N_3O_6W$, M_r=595.26, T=100(2) K, λ=1.54178 Å, crystal system, space group: monoclinic, $P2_1/c$,unit cell dimensions: a=10.0012(1), b=18.0404(1), c=12.7948 (1) Å, β=110.50 (0)°, V=2162.37(3) Å^3, Z=4, ρ_{calcd}=1.828 Mg m^{-3}, μ=10.275 mm^{-1}, $F(000)$=1160, crystal size: 0.18×0.12×0.06 mm^3, θ range for data collection: 4.43–70.37°, index ranges: $-11\le h\le 12$, $-20\le k\le 20$, $-15\le l\le 14$, reflections collected/unique=13686/3955 [R_{int}=0.0273], completeness to 2θ=70.37 (96.0%), absorption correction: empirical, refinement method: full-matrix least-squares on F^2, data/restraints/parameters=3955/0/365, goodness-of-fit on F^2=1.053, final R indices [$I>2\sigma(I)$]: R_1=0.0191, wR_2=0.0488, R indices (all data): R_1=0.0205, wR_2=0.0496; extinction coefficient=0.00028(2), largest difference peak and hole=0.568 and −1.256 e Å^{-3}. CCDC 289214 contains 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.

Acknowledgements

This research was partially supported by the Spanish and Principado de Asturias Governments (BQU-2001-3853 and GE-EXP01–11), MEC, and ESF (Juan de la Cierva contract to S.M.).

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Received: November 10, 2005
Published online: February 28, 2006

