

Dötz Benzannulation Reactions: Heteroatom and Substituent Effects in Chromium Fischer Carbene Complexes

J. Oscar C. Jimenez-Halla and Miquel Solà*^[a]

Abstract: We have carried out a theoretical investigation of the Dötz reaction between acetylene and a series of chromium Fischer-type carbenes $[(\text{CO})_5\text{Cr}=\text{C}(\text{X})\text{R}]$ with different representative substituents ($\text{R} = \text{CH}=\text{CH}_2$, Ph) and heteroatom ligands ($\text{X} = \text{OH}$, NH_2 , OCH_3 , $\text{N}(\text{CH}_3)_2$) by using density functional theory with the B3LYP functional. We have studied the Dötz and chromahexatriene mechanisms of benzannulation and also the reaction mechanism leading to cyclopentannulation. For the benzannulation, it was found that the most likely mechanism

in the case of vinylcarbenes is the chromahexatriene route, whereas for phenylcarbenes, the Dötz route via a ketene intermediate is clearly the most favorable. The reactions leading to the cyclopentannulated and benzannulated products are more exothermic with vinylcarbenes than with phenylcarbenes and also more exothermic with alkoxy-

carbenes than with aminocarbenes. The relative stability of the cyclopentannulated products as compared with the benzannulated products increases for bulkier X substituents and on going from alkoxy- to aminocarbenes. The kinetic data concurs with the experimental product distribution found for vinylcarbenes, by which mainly benzannulated products are obtained, and dimethylaminophenylcarbenes, which lead exclusively to cyclopentannulated adducts.

Keywords: annulation • carbenes • density functional calculations • Dötz reaction • reaction mechanisms

Introduction

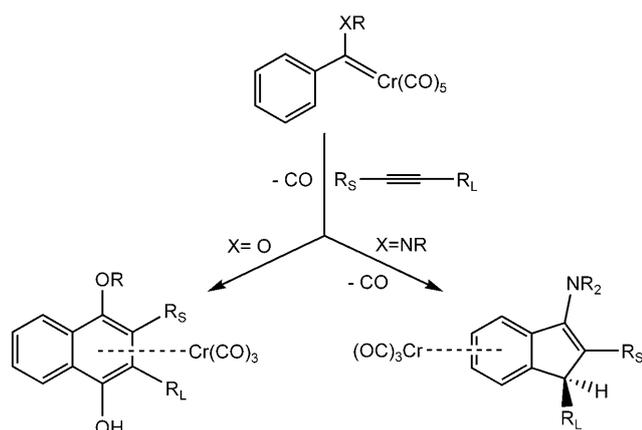
Since their discovery by Fischer and Maasböl in 1964,^[1] Fischer metal–carbene complexes of the general formula $[(\text{CO})_5\text{M}=\text{C}(\text{X})\text{R}]$ ($\text{M} = \text{Cr}, \text{Mo}, \text{W}$; $\text{X} = \text{a } \pi\text{-donor substituent}$; $\text{R} = \text{a saturated alkyl or unsaturated alkenyl, alkynyl, or aryl group}$) have developed from being exotic organometallic complexes to useful reagents with an extensive, versatile, rich, and fascinating chemistry.^[2,3] In this species, the $\text{Cr}=\text{C}_{\text{carbene}}$ bonding mechanism is similar to that of a metal–carbonyl bond; the carbene donates in a σ fashion to the metal and the metal back-donates to the unoccupied π orbitals of the carbene.^[3] However, at variance with the $\text{Cr}=\text{CO}$ bonding, donation is larger than back-donation in the $\text{Cr}=\text{C}_{\text{carbene}}$

bond.^[4] As a result, there is a lack of charge on the carbene carbon atom, which suggests a $[(\text{CO})_5\text{Cr}^{\delta-}-\text{C}^{\delta+}(\text{X})\text{R}]$ electronic distribution that explains the electrophilic nature of this atom in Fischer carbenes.^[5] In these complexes, the substituent X acts as a π donor that stabilizes the electron-deficient carbene atom, whereas the low-valent metal center is stabilized by π -acceptor substituents such as CO.^[4,6] The $\text{Cr}=\text{C}-\text{X}$ group forms a weak 3-center 4-electron bond.^[6] The first applications of these Group 6 heteroatom stabilized carbene complexes started around the 1970s^[7] and nowadays, after four decades, Fischer carbene chemistry has reached what could be considered a situation of creative maturity. These fascinating complexes are potential precursors of many functionalized carbo- and heterocycles through thermal and photochemical procedures.^[8–10]

First reported in 1975,^[11] the so-called Dötz benzannulation reaction can be regarded as the most important and synthetically useful of the Fischer carbene reactions (see refs. [12–14] for recent reviews). This reaction represents an efficient synthetic method that gives easy access to important antibiotics,^[15] natural products,^[16] and biologically interesting molecules.^[17] It involves the formation of an ensemble between an α,β -unsaturated pentacarbonylchromium–carbene complex and an alkyne to provide phenolic (Scheme 1,

[a] J. O. C. Jimenez-Halla, Prof. Dr. M. Solà
Institute of Computational Chemistry, University of Girona
Campus Montilivi, 17071 Girona, Catalonia (Spain)
Fax: (+34)972-418356
E-mail: miquel.sola@udg.edu

Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/chem.200901359>. Cartesian coordinates of all reactants, intermediates, and transition states on the PES described therein.



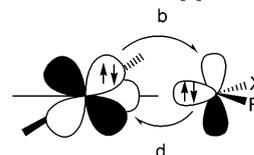
Scheme 1. Dötz benzannulation versus cyclopentannulation as the most common chromium-mediated cycloaddition reactions of Fischer carbene complexes in which R are alkyl substituents and R_S and R_L are the small and large alkyl or aryl substituents of the alkyne, respectively.

left-hand product) or indene derivatives (Scheme 1, right-hand product). Although these six- (6-MR) and/or five-membered ring (5-MR) products are the most frequently observed, up to 21 different types of species have been isolated and characterized in this cycloannulation reaction.^[14,18] Among them one finds quinones, indenones, furans, cyclobutanones, or cyclooctatrienones.^[19,20]

Relatively minor modifications to the structure of the Fischer carbene, the alkyne, or the reaction conditions can dramatically alter the product distribution of the reac-

tion.^[12–14,21] For instance, higher temperatures, smaller alkyne concentrations, the presence of noncoordinating solvents, and the use of terminal instead of internal alkynes and more sterically hindered alkynes as well as heavier transition metals of Group 6 are all factors that favor indene products over phenols.^[10,12–14,18,21] Moreover, a very important characteristic of the reaction is the π -donor nature of the X substituent in the Fischer carbene. Thus, when amino groups are used instead of alkoxy ligands, the ratio of cyclopentannulation to benzannulation is increased.^[13,14,22] This is related presumably to the better π -donor capacity of nitrogen compared with oxygen, as can be seen in Table 1

Table 1. Role of the heteroatom effect in the electron flow in Fischer carbenes. The data for the donation (d) and back-donation (b) (values given in italics) of electrons are taken from ref. [4].



X	R = H	R = CH=CH ₂	R = Ph
OH	0.499	0.507	0.503
	<i>0.255</i>	<i>0.215</i>	<i>0.249</i>
OCH ₃	0.528	0.522	0.513
	<i>0.244</i>	<i>0.206</i>	<i>0.243</i>
NH ₂	0.501	0.499	0.480
	<i>0.214</i>	<i>0.198</i>	<i>0.229</i>
NHCH ₃	0.511	0.502	0.486
	<i>0.218</i>	<i>0.191</i>	<i>0.214</i>

Abstract in Catalan: Hem dut a terme una investigació teòrica fent servir el mètode de la teoria del funcional de la densitat B3LYP sobre la reacció de Dötz entre l'acetilè i una sèrie de carbens de Fischer de crom [(CO)₅Cr=C(X)R] amb diferents substituents (R = CH=CH₂, Ph) i lligands amb heteroàtoms (X = OH, NH₂, OCH₃, N(CH₃)₂) representatius. Hem estudiat les rutes de la benzanul·lació de Dötz i del cromahexatriè així com el mecanisme de reacció que porta a la ciclo-pentannul·lació. Respecte a la benzanul·lació, s'ha trobat que el mecanisme més probable pel cas dels vinilcarbencs és la ruta del cromahexatriè mentre que, pels fenilcarbencs, la via proposada per Dötz que va a través d'un intermediari de tipus cetena està clarament més afavorida. Les reaccions que condueixen als productes de ciclo-pentannul·lació i benzanul·lació són més exotèrmiques en els vinilcarbencs que en els fenilcarbencs i també més exotèrmiques en els alcòxcarbencs que en els aminocarbencs. L'estabilitat relativa dels productes de la ciclo-pentannul·lació comparada amb els de la benzanul·lació s'incrementa quan substituents X són més grans i quan es canvia de alcòxcarbencs a aminocarbencs. Les dades cinètiques lliguen amb la distribució experimental de productes que s'ha trobat en els vinilcarbencs, pels quals els productes de benzanul·lació són els que s'obtenen amb més quantitat i també pel cas de dimetilamino-fenilcarbencs on es formen exclusivament adductes de ciclo-pentannul·lació.

(values for the X = N(CH₃)₂ species were not included in the study of ref. [4]). Our group has shown that, as expected from the Dewar–Chatt–Ducanson model,^[23] the stronger the π -donor character of the X group, the smaller the back-donation from the metal to the carbene, as can be seen from the values in Table 1.^[3,4,24] As a result of the reduced metal-to-carbene back-donation in strong π donors, the back-donation from the metal to the CO ligands becomes larger, which makes the Cr–CO bonds stronger and the insertion of CO into the new ring more difficult.^[25] This is referred to as the heteroatom effect and it concurs with the experimental observation that less electron-poor chromium–carbenes require harsher conditions for the initial decarbonylation step of the Dötz reaction.^[13,14] However, during the last decade many cases in which this explanation has not been enough to explain why cyclopentannulation is favored over benzannulation have been reported.^[10,26–29] The values for back-donation in Table 1 also indicate that phenylcarbenes have slightly larger back-donation than vinylcarbenes (CH=CH₂ is a somewhat better π -donor than Ph^[30]). Indeed, the R group can also have an enormous influence on the product distribution. For instance, it has been found that dialkylaminoarylcabenens give exclusively indenenes,^[13,21,27,31] whereas dialkylaminovinylcarbenes yield phenols and cyclohexadienones.^[27,31]

A deeper understanding of the reaction mechanisms that direct the formation of the different products obtained in the Dötz reaction would be highly desirable to achieve a better control of the reaction outcome.^[5,32,33] To obtain this knowledge from experiments only is rather difficult because the rate-limiting step of this process involves the loss of CO to provide a coordination site for the alkyne. Then, once the alkyne is bound, very fast ring closure takes place, which makes characterization of reaction intermediates very complicated. The use of computational tools in such cases is highly recommended to help in elucidating the reaction mechanisms.^[34,35] Indeed, some mechanistic details of this paradigmatic reaction have already been investigated from a theoretical point of view by our group^[36–38] and by others.^[39,40]

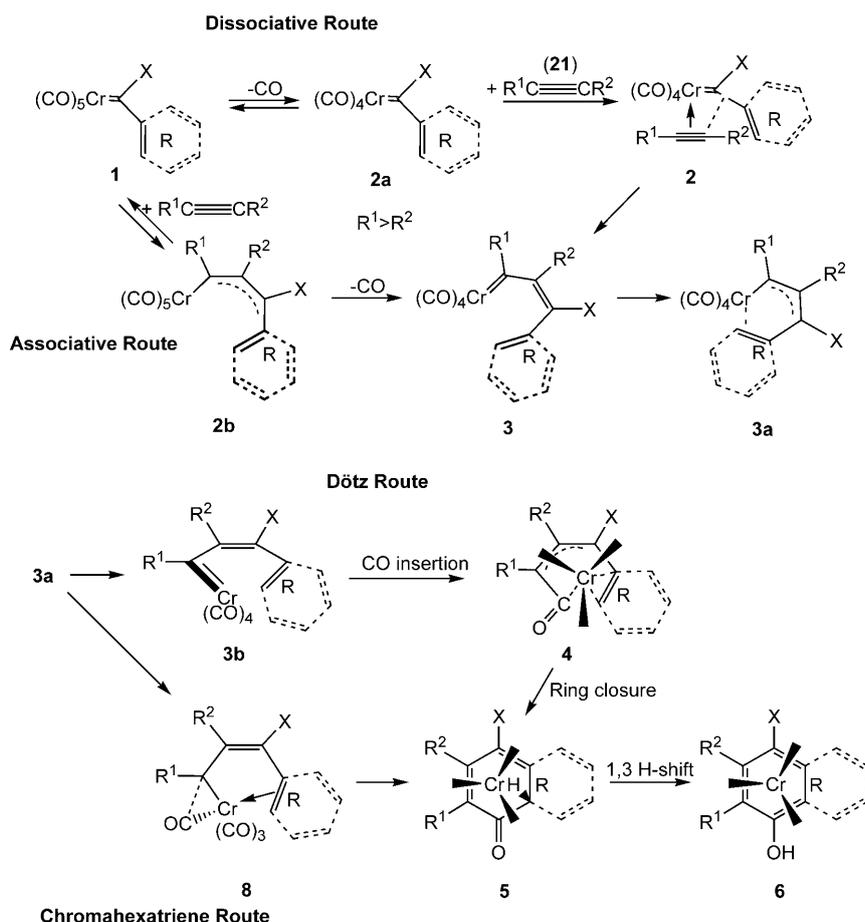
Scheme 2 shows the most viable reaction mechanism proposals explored in these previous works. Essentially, the reaction begins with CO dissociation and alkyne insertion into the metal sphere of the vinylcarbene **1**. It is well documented that this thermally reversible stage is the rate-limiting step^[20,41] in the Dötz reaction. Depending on the order of events, it has been postulated that an initial CO dissociation in **1** leads to the unsaturated 16-electron species **2a** and subsequent alkyne coordination (**2**) and insertion into the car-

bene–metal bond (**3**) produces an α,β -unsaturated vinyl- or phenylcarbene **3a** (dissociative route).^[42,43] Another possibility for this initial part of the reaction is alkyne insertion into **1** leading to the 17-electron intermediate **2b** followed by CO dissociation to also give the species **3** (associative route).^[44,45] In the central part of the reaction, under the Dötz benzannulation mechanistic proposal, there is first a rearrangement of carbene **3a** into **3b** (bending of the Cr–C(α) bond to place one of the CO ligands closer to the α -carbon atom) followed by a CO insertion to form **4**, an η^3 -vinylketene (or phenylketene) complex. Then, electrocyclic ring closure of **4** to form **5** followed by tautomerization generates **6**, an η^6 -benzenic (or naphthalenic) Cr(CO)₃ complex (Scheme 2). A decade ago, our group proposed that from vinylcarbene **3a**, the π interaction with the terminal C=C double bond of the carbene affords a chromahexatriene complex that allows an earlier C(α)–CO interaction in **8** that leads to the η^4 -cyclohexadienone **5** in the next step.^[36] A third possibility suggested by Casey,^[46] in which the metalation of **3a** occurs directly and then CO insertion takes place originating a chromacycloheptadienone species, will not be discussed here because on the basis of all our previous^[34,47] and present calculations this reaction mechanism is significantly much higher in energy than the aforementioned proposals.

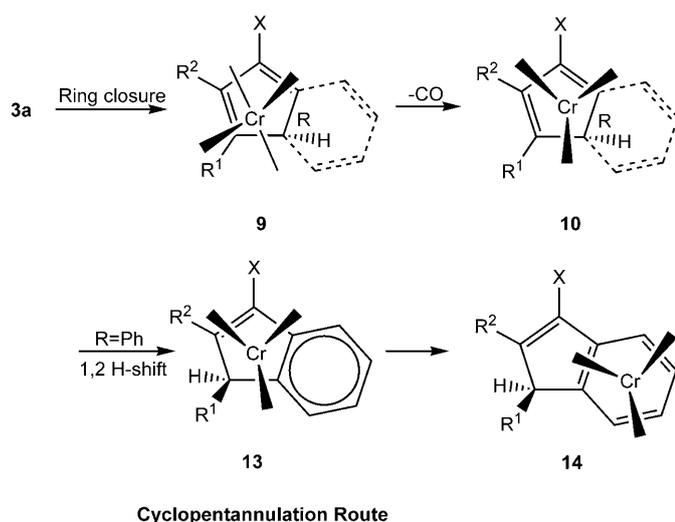
The reaction mechanisms

leading to the formation of the 5- and 6-MRs are the same until complex **3a** is reached. From this point there is a ramification and either 6- or 5-MRs are obtained depending on the incorporation or not of carbon monoxide into the ring. Scheme 3 illustrates the competitive reaction that leads to 5-MR, which we also broach in this work. By closing the ring (**9**) and subsequently removing CO, indene **10** is obtained. For phenylcarbenes, a 1,2-H shift to a more stabilized position, which can be assisted or not by the solvent, leads to **13**.^[9,10,28,48] Finally, a haptotropic rearrangement results in the formation of **14** as the final product. Recent advances relating to the versatility of both reactions^[49] have prompted us to investigate the reaction mechanisms for the formation of phenols and indenenes in the Dötz reaction.

Therefore, we have carried out a theoretical mechanistic investigation of the reaction



Scheme 2. Mechanisms for the benzannulation reaction of Fischer carbenes.



Scheme 3. Mechanism for the cyclopentannulation reaction of Fischer carbene **3a**.

pathways leading to the two more usual products of the Dötz reaction (phenols and indenenes) by using density functional theory (DFT) with Fischer carbenes bearing representative substituents ($R = \text{CH}=\text{CH}_2$, Ph) and heteroatom ligands ($X = \text{OH}$, NH_2 , OCH_3 , $\text{N}(\text{CH}_3)_2$) with a two-fold purpose: 1) to investigate the heteroatom and substituent effects in these reaction mechanisms (Schemes 2 and 3) and 2) to discuss the origin of the experimental product distributions found in these reactions. Gleichmann, Dötz, and Hess (GDH)^[39] investigated the reaction of Fischer carbenes with $X = \text{OH}$ and NH_2 and $R = \text{CH}=\text{CH}_2$ and Ph that lead to 6-MR formation. However, they analyzed only the Dötz route in Scheme 2. Thus, in this work we extend their study by including four new systems (the species with $X = \text{OCH}_3$ and $\text{N}(\text{CH}_3)_2$) and by analyzing two new reaction pathways: The chromahexatriene and cyclopentannulation routes. In this way, we expect to gain a deeper understanding of the reasons for the product distributions obtained experimentally.

Results and Discussion

This section is divided as follows: first, the results for the initial part of the reaction (**1**→**3a**) are presented and, second, we discuss the product distributions in cycloannulation reactions with special emphasis on the three reaction mechanisms analyzed (Schemes 2 and 3).

Initial part of the reaction: Pentacarbonylchromiumcarbenes (**1**) as starting points for this reaction have been discussed in the literature in terms of reactivity and bonding.^[4,6,50] In this work we performed a conformational study of the studied alkoxy Fischer carbenes following the previous work on the pentacarbonyl(hydroxyvinylcarbene)chromium(0).^[37]

Alkoxy metal carbenes present two conformations: *anti* (alkoxy ligand towards $\text{Cr}(\text{CO})_5$ in a staggered position with

respect to the carbonyls) and *syn* (alkoxy ligand pointing towards the R substituent). The calculated Gibbs free energies for both kinds of isomers are given in Table 2. Clearly the

Table 2. Relative Gibbs free energies^[a] (ΔG_{298}^0) for the *anti* and *syn* conformations of the hydroxycarbenes studied herein calculated at the B3LYP/(Wachters' basis,6-31G(d,p)) level of theory.

	$X' = \text{H}$	$X' = \text{CH}_3$
	ΔG_{298}^0 [kcal mol ⁻¹]	ΔG_{298}^0 [kcal mol ⁻¹]
$R = \text{CH}=\text{CH}_2$	3.6	4.8
$R = \text{Ph}$	2.9	2.1

[a] Values computed as $\Delta G = G_{\text{syn}} - G_{\text{anti}}$.

anti conformer prevails over the *syn* orientation as has already been found experimentally for the methoxy-(methyl)carbene complex.^[51] Fernández et al.^[52] have demonstrated that this bias in the case of $X' = \text{CH}_3$ is due to a two-electron stabilizing donation from the σ_{CH} orbital of the alkoxy group to the π_{CO}^* of the closer CO ligand and back-donation from the π_{CO} orbital to the σ_{CH}^* orbital in the *anti* isomer as well as to the stronger destabilizing repulsion between the OX' group and the R substituent present in the *syn* conformer. Both experimental data and the theoretical calculations show that there is a free rotation around the $\text{C}_{\text{carbene}}-\text{OX}'$ bond under mild conditions with energy barriers of about 11–14 kcal mol⁻¹.^[37,51,52] There is also almost free rotation around the $\text{Cr}=\text{C}_{\text{carbene}}$ bond for which the staggered conformation (the plane of the carbene bisects the plane containing two carbonyls) is somewhat more stable than the eclipsed conformation.^[37,53,54]

We analyzed both the dissociative and associative scenarios shown in Scheme 2 (see above). In the case of the dissociative pathway, in which carbon monoxide loss takes place, we explored all the possible intermediates, that is, elimination of the *trans*-CO ligand with respect to the carbene or the four *cis*-CO positions. We found that removal of a *trans*-CO is higher in energy by around 7 kcal mol⁻¹ (on average) than removal of the *cis*-COs, in agreement with experimental and theoretical observations.^[18,37,39,55] Two square-pyramidal conformers result from *cis* elimination depending on whether the CO removed is closer to the heteroatom (**2a-1**) or the R substituent (**2a-2**; Figure 1). The energy difference between the **2a-1** and **2a-2** isomers in $[(\text{CO})_4\text{Cr}=\text{C}(\text{X})\text{CHCH}_2]$ carbenes is 3.9, 2.3, 2.2, and 0.4 kcal mol⁻¹ for $X = \text{OH}$, NH_2 , OCH_3 , and $\text{N}(\text{CH}_3)_2$, respectively, whereas for $[(\text{CO})_4\text{Cr}=\text{C}(\text{X})\text{Ph}]$ the difference is 5.2, 4.0, 2.4, and 3.9 kcal mol⁻¹, respectively. Interestingly, the energy differences between **2a-1** and **2a-2** for the alkenyl- and arylaminocarbenes are bigger (1.7–3.5 kcal mol⁻¹) than for the corresponding alkoxy-carbenes (less than 1.3 kcal mol⁻¹). The dissociation leading to **2a-2** is more favorable because of

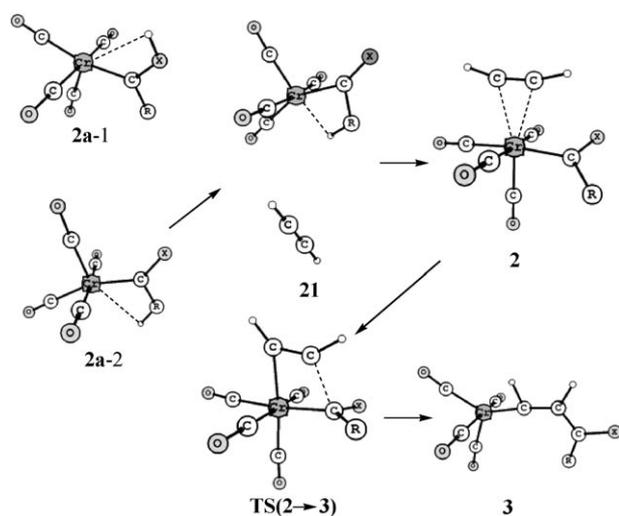
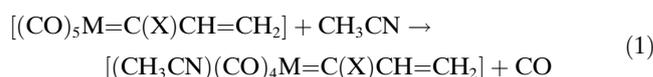


Figure 1. Scheme for acetylene insertion into $\text{Cr}(\text{CO})_4$ carbenes by the dissociative route for $\text{X}=\text{OH}$, OCH_3 , NH_2 , and $\text{N}(\text{CH}_3)_2$ and $\text{R}=\text{CHCH}_2$ and Ph . For the structures of **2a-1**, **2a-2**, and **21**, the hydrogen atoms are shown explicitly for the X or R groups. TS=transition state.

the agostic interaction formed between the C–H bond of the vinyl group (or phenyl for alkoxy-carbenes) and the vacant site in the chromium Fischer carbene complex.^[37] Thus, taking into account this second isomer of **2a**, the C–H bond distance increases by about 0.015–0.032 Å on going from **1** to **2a-2** depending on the Fischer carbene considered. This agostic interaction is responsible for the gain of stability, which is estimated to be about 5–10 kcal mol⁻¹ on the basis of values obtained for similar complexes,^[56] which thus explains the higher stability of species **2a-2**. The X-ray data for a tetracarbonyl(methoxyarylcarbene)chromium(0) complex equivalent to **2a-2** was reported by Dötz and co-workers in 1997.^[57] The Gibbs free energies (the enthalpies are given in parentheses) and energy barriers for the dissociation process **1**→**2a-2** are collected in Table 3. For the $[(\text{CO})_5\text{Cr}=\text{C}(\text{OCH}_3)\text{Ph}]$ complex, the experimental values^[42] of (26 ± 0.5) kcal mol⁻¹ and (6 ± 1.5) cal K⁻¹ mol⁻¹ for the dissociation enthalpy and entropy are in good agreement with our values (23.5 kcal mol⁻¹ and 7.0 cal K⁻¹ mol⁻¹). As GDH found for $\text{X}=\text{OH}$ and NH_2 ,^[39] our results also show that substitution of $\text{X}=\text{OX}'$ by $\text{X}=\text{NX}'_2$ has a minor effect (change of 1–2 kcal mol⁻¹ in ΔG or ΔH) on the dissociation energy of *cis*-CO. The so-called heteroatom effect is clearly seen in the dissociation of *trans*-CO, which increases in the expected order of increasing π -donor character of the X groups ($\text{OH} < \text{OCH}_3 < \text{NH}_2 < \text{N}(\text{CH}_3)_2$, with the only exception being an interchange between OCH_3 and NH_2 in the ordering for $\text{R}=\text{Ph}$), but not in the *cis*-CO dissociation. It is worth mentioning that substitution of H by CH_3 in the alkoxy X ligands reduces the dissociation energy by about 4 kcal mol⁻¹. It is quite likely that a bulkier group in the alkoxy substituent enables the vinyl or the phenyl R group to be closer to the metal and form stronger agostic interactions (for instance, the $\text{Cr}\cdots\text{H}_{\text{phenyl}}$ bond in $[(\text{CO})_4\text{Cr}=\text{C}(\text{X})\text{Ph}]$ changes from 2.524 to 2.312 Å on going from $\text{X}=\text{OH}$ to $\text{X}=\text{OCH}_3$).

changes from 2.524 to 2.312 Å on going from $\text{X}=\text{OH}$ to $\text{X}=\text{OCH}_3$). Note also that dissociation is somewhat easier in phenylcarbenes than in vinylcarbenes, which in this case concurs with the fact that vinylcarbenes are stronger π donors than phenylcarbenes. Unlike GDH, who did not find TSs for these dissociation processes,^[39] we have located the TSs for the eight *cis*-CO dissociation processes. The trends observed in energy barriers are similar to those found for the dissociation energies (Table 3). The most important difference, due to the heteroatom effect, in the energy required to surmount energy barriers is now more evident as Gibbs free energies and enthalpy barriers to the loss of carbon monoxides from alkoxy-carbenes are 5–10 kcal mol⁻¹ larger than those from aminocarbenes. The energy barriers required to remove one *cis*-CO from chromium in these carbene follows the sequence $\text{N}(\text{CH}_3)_2 < \text{NH}_2 < \text{OH} \approx \text{OCH}_3$. This result does not conform to the experimental observation that stronger π donors in chromium carbenes require harsher conditions for the initial decarbonylation step of the Dötz reaction.^[13,14] For this reason, we have calculated the *cis*-CO dissociation energies for $[(\text{CO})_5\text{Cr}=\text{C}(\text{X})\text{CH}=\text{CH}_2]$ for $\text{X}=\text{OH}$ and NH_2 by using different methods and basis sets. The results collected in Table S1 of the Supporting Information confirm that differences in dissociation Gibbs free energies are less than 2 kcal mol⁻¹ on going from $\text{X}=\text{OH}$ to $\text{X}=\text{NH}_2$. Apparently, this discrepancy between experimental and theoretical results is solved when one considers the presence of donating solvents such as tetrahydrofuran, acetonitrile, or diethyl ether. In this case, the *cis*-CO-solvent exchange process clearly favors dissociation in Fischer carbenes having stronger π donors, as demonstrated by GDH.^[39] We confirmed this result by calculating the Gibbs free energy of the dissociation process for $\text{X}=\text{OH}$ and NH_2 by using Equation (1):



We found that this exchange process requires 12.7 kcal mol⁻¹ for $\text{X}=\text{OH}$ and 14.5 kcal mol⁻¹ for $\text{X}=\text{NH}_2$. The endergonicity of this process indicates that the interaction of $[(\text{CO})_4\text{M}=\text{C}(\text{X})\text{CH}=\text{CH}_2]$ with CO is larger than with CH_3CN , as one would expect from the higher σ -donor-plus- π -acceptor character of the former.^[58] The difference in the interaction energy between CO and CH_3CN coordination increases in less electron-poor carbenes, that is, on going from $\text{X}=\text{OH}$ to NH_2 .

Once **2a-2** is formed, the acetylene molecule approaches the metal complex to form the van der Waals complex **21** (see Figure 1) and preactivate the following insertion scenario. Complex **21** is stabilized with respect to **2a-2** and acetylene from -4.7 to 0.2 kcal mol⁻¹ in terms of enthalpy, although it is thermodynamically unstable according to Gibbs free-energy values (from 3.8–6.1 kcal mol⁻¹). This chromium-acetylene interaction is generally a little more favored for alkoxy- than for aminocarbenes and is also more favored for vinyl- than for phenylcarbenes. Note that the energy

Table 3. Reaction free energies (ΔG_{298}^0) and activation barriers ($\Delta G_{298}^{0 \ddagger}$) for all steps in the initial stages of the reaction calculated at the B3LYP/(Wachters' basis, 6-31G(d,p)) level (enthalpy values, ΔH_{298}^0 and $\Delta H_{298}^{0 \ddagger}$, are given in parentheses).^[a]

Route	Step	ΔG_{298}^0 (ΔH_{298}^0)		TS	$\Delta G_{298}^{0 \ddagger}$ ($\Delta H_{298}^{0 \ddagger}$)			
R = CH=CH ₂								
Ds	1→2a	X = OH	X = NH ₂	TS(1→2a)	X = OH	X = NH ₂		
	2a→2b	19.2 (30.3)	19.0 (31.6)		31.3 (35.1)	26.1 (32.1)		
	2b→2c	3.8 (-4.7)	4.2 (-3.3)					
	2c→2d	0.9 (-1.6)	-3.1 (-6.2)					
As	2→3	-29.7 (-30.0)	-25.5 (-25.6)	TS(2→3)	4.5 (2.3)	10.1 (8.2)		
	1→20	7.5 (1.2)	3.1 (-0.4)	TS(20→2b)	34.2 (29.1)	31.5 (28.0)		
	20→2b	-24.0 (-29.4)	-19.9 (-25.7)					
	2b→3	10.8 (22.2)	11.3 (22.7)				TS(2b→3)	23.2 (26.6)
3→3a	0.5 (1.5)	1.7 (0.1)	TS(3→3a)				0.6 (1.2)	1.8 (0.3)
Ds	1→2a	X = OCH ₃	X = N(CH ₃) ₂	TS(1→2a)	X = OCH ₃	X = N(CH ₃) ₂		
	2a→2b	15.2 (26.3)	15.0 (26.2)		32.1 (36.0)	22.0 (26.8)		
	2b→2c	6.1 (-0.2)	6.0 (0.2)					
	2c→2d	4.0 (0.2)	2.2 (-2.4)					
As	2→3	-33.4 (-34.2)	-31.4 (-31.4)	TS(2→3)	3.9 (1.8)	11.6 (10.0)		
	1→20	9.9 (3.9)	5.5 (-0.1)	TS(20→2b)	35.8 (35.6)	32.0 (31.8)		
	20→2b	-30.8 (-36.1)	-22.5 (-28.0)					
	2b→3	12.8 (24.2)	8.8 (20.7)				TS(2b→3)	23.0 (26.1)
3→3a	-0.1 (-2.1)	2.7 (1.4)	TS(3→3a)				0.7 (0.0)	2.6 (1.7)
R = Ph								
Ds	1→2a	X = OH	X = NH ₂	TS(1→2a)	X = OH	X = NH ₂		
	2a→2b	15.6 (27.6)	17.0 (28.8)		29.5 (33.3)	24.3 (29.6)		
	2b→2c	4.1 (-3.8)	5.6 (-1.1)					
	2c→2d	4.4 (0.6)	-0.4 (-5.4)					
As	2→3	-32.6 (-32.8)	-28.4 (-28.1)	TS(2→3)	4.8 (3.1)	10.6 (9.1)		
	1→20	8.3 (1.1)	5.7 (-1.2)	TS(20→2b)	42.1 (43.5)	37.3 (37.4)		
	20→2b	-23.4 (-27.4)	-19.9 (-23.5)					
	2b→3	6.7 (17.9)	7.9 (29.3)				TS(2b→3)	27.4 (29.1)
3→3a	2.4 (1.1)	2.7 (2.0)	TS(3→3a)				2.6 (1.1)	2.7 (2.2)
Ds	1→2a	X = OCH ₃	X = N(CH ₃) ₂	TS(1→2a)	X = OCH ₃	X = N(CH ₃) ₂		
	2a→2b	11.2 (23.5)	10.5 (22.0)		25.2 (31.1)	18.7 (22.8)		
	2b→2c	6.0 (-0.1)	6.0 (-1.4)					
	2c→2d	4.1 (0.5)	7.1 (3.2)					
As	2→3	-25.4 (-28.7)	-32.3 (-32.2)	TS(2→3)	5.2 (2.3)	10.9 (9.0)		
	1→20	6.5 (0.5)	6.0 (-1.1)	TS(20→2b)	42.5 (43.3)	31.4 (32.4)		
	20→2b	-24.2 (-27.7)	-22.2 (-26.6)					
	2b→3	13.6 (22.4)	7.5 (19.2)				TS(2b→3)	23.7 (26.0)
3→3a	-6.5 (-6.1)	3.1 (2.0)	TS(3→3a)				1.6 (1.2)	3.3 (2.3)

[a] For notation of the structures, see Scheme 2. All energies are in kcal mol⁻¹.

values corresponding to the formation of **21** from **2a-2** and acetylene are likely to be underestimated by most current DFT methods and, in particular, by the B3LYP method used in this work.^[59] Subsequent coordination of acetylene leads to species **2**. Note the twisting of the hydrogen to a *syn* position in **2**; some time ago *anti*→*syn* conversion before loss of CO was reported.^[60] The substitution of CO by C₂H₂ in complex **1** to give **2** is an endothermic and endergonic process, which indicates that CO is a better σ donor and π acceptor than acetylene. Finally, **2** evolves into **3** via a chromacyclobutadiene-like TS(**2**→**3**) structure. The barrier associated with this transformation is relatively low and is higher by 5–7 kcal mol⁻¹ for the alkoxy-carbenes compared with the aminocarbenes (as expected, the more electron-deficient C_{carbene} atoms insert acetylene more easily).

In the associative pathway, first, the thermodynamically unstable (basically for entropic reasons) structure **20** is

formed, which arises from the interaction between Cr(CO)₅-carbene **1** and a weakly interacting acetylene (see Figure 2). Direct insertion of the acetylene into **20** via TS(**20**→**2b**) leads to intermediate **2b**, which has the lowest minimum energy for this initial part of the reaction in all cases. For Fischer carbenes with R=Ph, the Gibbs free energy and enthalpy barriers for the **20**→**2b** transformation are higher than those corresponding to the whole **2a**→**3** conversion, thus making this associative pathway unlikely in these cases. However, for R=CH=CH₂ the TSs are less congested and the differences between associative and dissociative pathways become smaller.^[47] Indeed, in general, the dissociative pathway presents lower Gibbs free energies but higher enthalpy barriers. Therefore, it is less easy to draw conclusions in this case, and the associative path may be perfectly operative. This is in line with the experimental finding that usually the Dötz reaction is first order in the carbene complex and zero order in the alkyne,^[42,43,61] as expected in a dissociative mechanism, although, depending on the reaction conditions, the reaction can be bimolecular with a first-order depend-

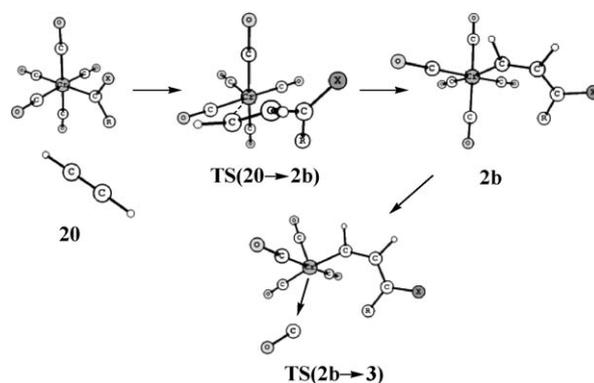


Figure 2. Scheme for acetylene insertion into Cr(CO)₄ carbenes by the associative route when X=OH, OCH₃, NH₂, N(CH₃)₂ and R=CHCH₂ and Ph.

ence on both the carbene complex and the alkyne.^[45] Finally, it is worth mentioning that the preference for the associative pathway increases for π -donor-substituted alkynes.^[42]

Vinyl- or phenylcarbene **3** then rearranges into the agostic complex **3a** (see below, Figure 4) in which the tail of the R substituent interacts agostically with the chromium atom. This conversion, which was calculated to proceed with energy barriers of about 2 kcal mol^{-1} , is a slightly endothermic and endergonic process for most of the cases (see Table 3). Alkoxycarbenes undergo this transformation more easily than aminocarbenes. Indeed, the Cr–H and Cr–C(methylene) distances in **3a** are shorter in alkoxycarbenes (1.909 and $2.426 \pm (0.02) \text{ \AA}$ in average, respectively) than in the aminocarbenes (1.934 and $2.441 \pm (0.02) \text{ \AA}$ in average, respectively). This is especially true for the case of the phenyl substituents. Thus, tetracarbonyl(hydroxyphenyl)chromium has a clear agostic interaction with the C(ϵ)–H bond (Cr–H 2.060 \AA and Cr–C(arene) 2.655 \AA), whereas for tetracarbonyl(aminophenyl)chromium the interaction is minor (Cr–H 2.875 \AA and Cr–C(arene) 2.855 \AA). This behavior is even more pronounced between tetracarbonyl(methoxyphenyl)chromium and tetracarbonyl(dimethylaminophenyl)chromium in which the Cr–H and Cr–C(arene) distances are 2.091 and 2.650 \AA versus 3.022 and 2.892 \AA , respectively. Moreover, $\text{Cr}(\text{CO})_4$ -methoxyphenylcarbene involves an exothermic and exergonic step to give **3a** in a clear opposite trend to that of the amino derivative (enthalpies (Gibbs free energies) -6.1 (-6.5) against $2.0 \text{ kcal mol}^{-1}$ ($3.1 \text{ kcal mol}^{-1}$), respectively). Thus, this point deserves special attention because it can be seen that alkoxycarbenes coordinate better than aminocarbenes to the coordinatively unsaturated metal center once a carbon monoxide is lost. Complex **3a** is the ramification point at which the next competing reactions of the cycloannulation diverge. As we will show in the next sections, all the following reaction steps have relatively low energy barriers and, therefore, the *cis*-CO dissociation (involving or not solvent exchange) must be considered as the rate-determining step.

Chromium-mediated cycloannulation reactions of the Fischer carbenes: We have split the presentation of the results of the second part of the reaction mechanism into two subsections: First, the reaction pathways of the benzannulation and cyclopentannulation reactions are discussed for the vinylcarbenes and the different X groups considered and then the same analysis is performed for the phenylcarbenes.

Vinylcarbenes: Figure 3a and b depict the Gibbs free-energy diagrams for hydroxyvinylcarbene and aminovinylcarbene **1** and Figure 3c and d show the Gibbs free-energy diagrams for methoxyvinylcarbene and dimethylaminovinylcarbene. In the classic Dötz proposal, the so-called vinylketene route (route A in Figure 3) entails an endothermic and endergonic arrangement of the η^1 -vinylcarbene **3a** to yield **3b**, which can be described as an η^3 -vinylcarbene (see Figure 4), prior to CO insertion into the Cr–C(α) bond. Conversion from **3a** to **3b** involves rotation and folding of the organic chain. In

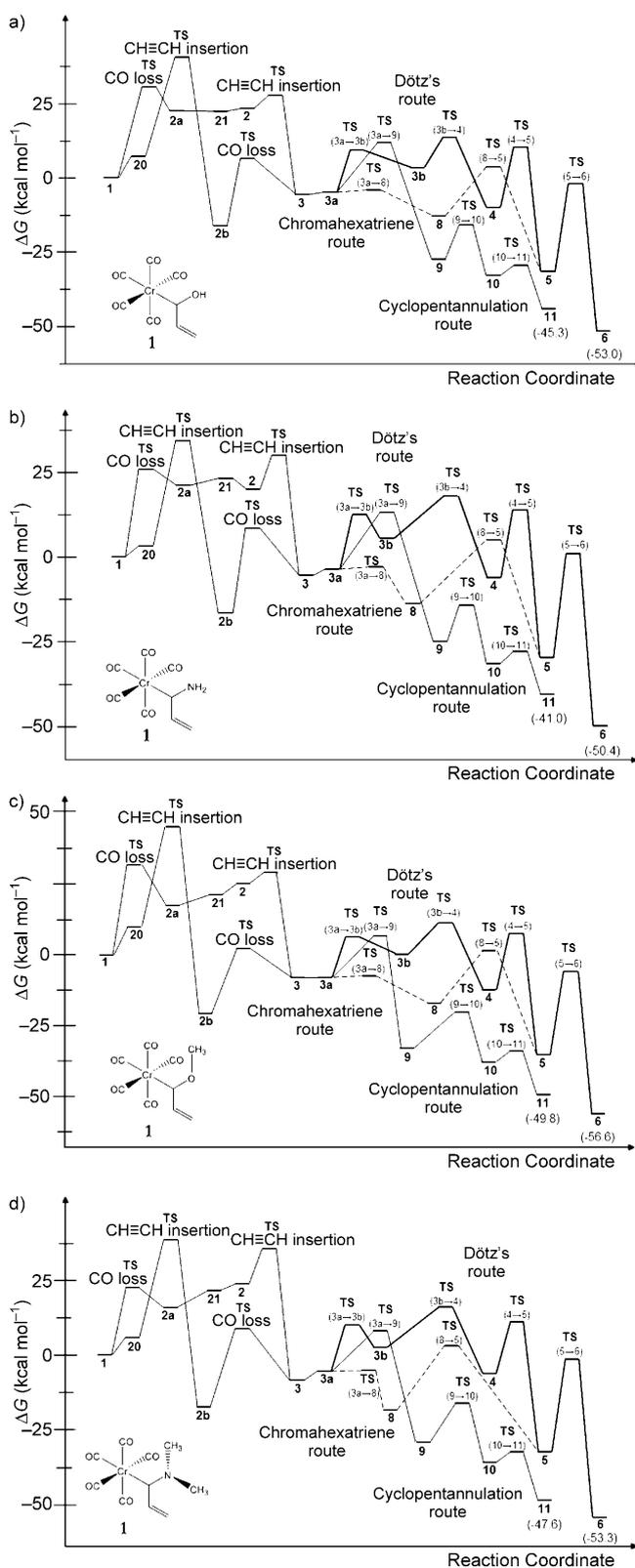


Figure 3. Gibbs free-energy profiles for the Fischer carbenes a) $[(\text{CO})_5\text{Cr}=\text{C}(\text{OH})\text{CHCH}_2]$, b) $[(\text{CO})_5\text{Cr}=\text{C}(\text{NH}_2)\text{CHCH}_2]$, c) $[(\text{CO})_5\text{Cr}=\text{C}(\text{OMe})\text{CHCH}_2]$, and d) $[(\text{CO})_5\text{Cr}=\text{C}(\text{NMe}_2)\text{CHCH}_2]$. Comparison of the studied mechanisms (benzannulation: route A, solid line; route B, dashed line; cyclopentannulation: route C, normal line). Relative energies are given in kcal mol^{-1} .

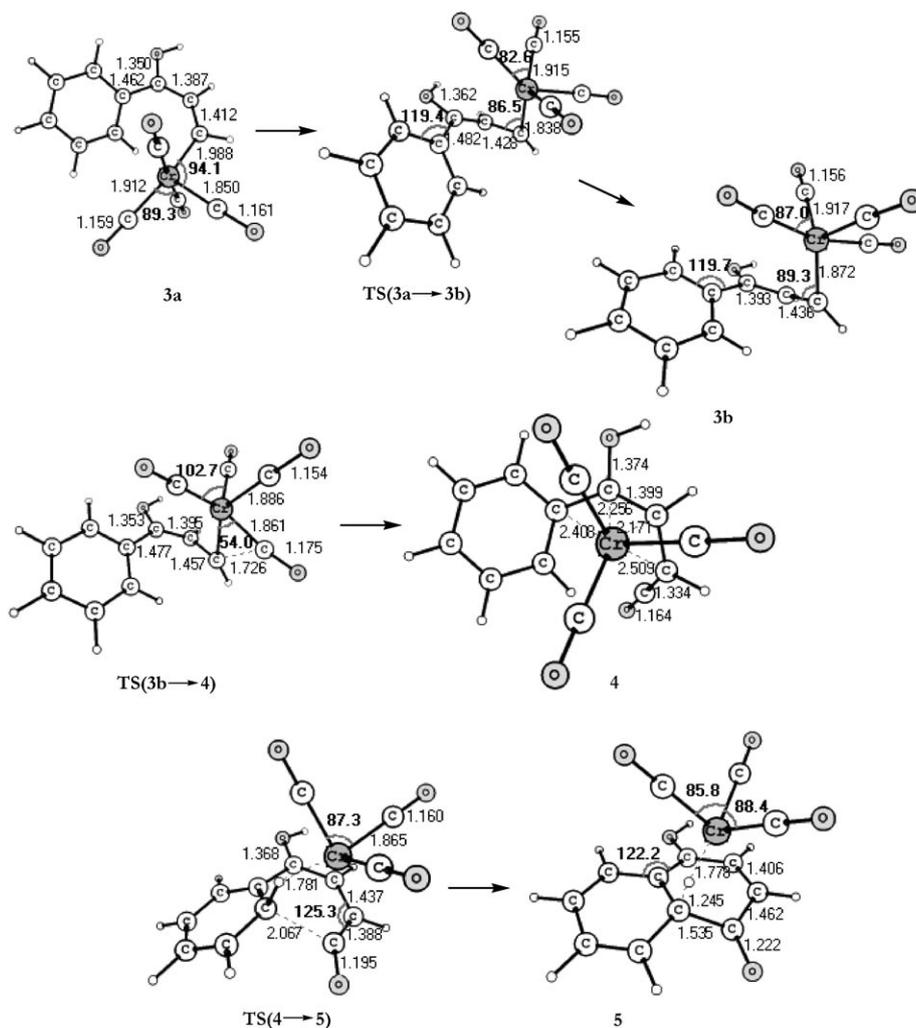


Figure 4. Optimized structures of intermediates and transition states in the Dötz benzannulation route for the case of X=OH and R=Ph. Distances in Å and angles in degrees.

this rearrangement the agostic interaction present in **3a** is lost and the vacant coordination site is partially filled through the π interaction with the C(β)C=C(δ) double bond. This isomerization is characterized by \angle CrC(α)C(β) angles of 88° (alkoxy derivatives) and 92° (amino derivatives). This step has similar energy requirements for the alkoxy- and aminocarbenes (see Table 4). This is probably because the **3a**→**3b** transformation does not involve strong bond-breaking/formation processes. Indirect support for intermediates **3a** and **3b** was provided by Barluenga and co-workers, who isolated a chromium–vinylaminocarbene complex having a molecular structure intermediate between a strict η^1 - and η^3 -bonded species.^[5,31,62] The step **3b**→**4** is clearly favored for the alkoxy carbene over the aminocarbene species (barriers are lower by as much as 8 kcalmol⁻¹ for X=OR species, as shown in Table 4). This clear heteroatom effect is the result of stronger π donors leading to strong CO bonds in **3b**.^[27] In fact, we calculated the Cr–CO bond strength in **3b** to be around 4 kcalmol⁻¹ stronger in

aminocarbenes than in alkoxy-carbenes. The next steps from η^4 -vinylketene **4** to the benzannulated product **6** show relatively minor heteroatom effects with almost no difference in the reaction energies and barriers for alkoxy- and aminocarbenes. This route has been supported by experimental observations of structures akin to **4**^[62,63] and the Wheland intermediate **5**^[18] in the past (see Scheme 2). Finally, a 1,3-hydrogen shift in **5** leads to **6** with a significant energy barrier. It is likely that the solvent can help in this process by subtracting the transferred proton and attaching it to the oxygen atom of the carbonyl group. Moreover, by considering the tunneling effect, the **5**→**6** energy barrier could also be reduced.

Our group proposed another mechanistic possibility some years ago, the so-called chromahexatriene route.^[36] Looking at the values in Table 4, we can say this alternative pathway is slightly more favorable than the Dötz reaction mechanism for benzannulation. The chromahexatriene intermediate **8** (see below, Figure 7) is formed from **3a** through very small energy barriers (less

than 1 kcalmol⁻¹) in a clearly exothermic and exergonic process. This kind of intermediate with an η^2 coordination mode^[64] cannot be discarded because it has been suggested in the literature that the insertion of alkynes into the Cr=C bond readily leads to structures that undergo subsequent cyclization reactions.^[64] Further evidence to support this route comes from an investigation by Barluenga et al.^[31] in which a species analogous to the chromahexatriene intermediate **8** was synthesized from the reaction of a tetracarbonyl(aminovinylcarbene)chromium(0) complex with dimethyl acetylenedicarboxylate and characterized by ¹H and ¹³C NMR spectroscopy. The authors also showed that decomposition of this intermediate produced cyclopentadienes and phenol derivatives.^[31] The next step in this chromahexatriene route is the **8**→**5** conversion (see Figure 7 below), that is, closing of the ring and the displacement of tricarbonylchromium to its center. The particular orientation of the carbene ligand in **8** favors the migration of CO because, during the transformation, each of the two π^* orbitals of

Table 4. Reaction free energies (ΔG_{298}^0) and activation barriers ($\Delta G_{298}^{\ddagger}$) for all steps in the benzannulation (Dötz route, A, and chromahexatriene route, B) and cyclopentannulation (C) reaction pathways calculated at the B3LYP/(Wachters' basis, 6-31G(d,p)) level of theory (enthalpy values, ΔH_{298}^0 and $\Delta H_{298}^{\ddagger}$, are given in parentheses). Results are presented for R=CH=CH₂ and for the different X substituents studied.^[a]

Route	Step	ΔG_{298}^0 (ΔH_{298}^0)		TS	$\Delta G_{298}^{\ddagger}$ ($\Delta H_{298}^{\ddagger}$)	
		X=OH	X=NH ₂		X=OH	X=NH ₂
A	3a → 3b	8.5 (9.6)	9.2 (10.2)	TS(3a → 3b)	14.5 (14.6)	16.2 (16.1)
	3b → 4	-13.7 (-15.8)	-11.8 (-14.2)	TS(3b → 4)	10.6 (9.4)	18.2 (16.5)
	4 → 5	-22.2 (-24.3)	-23.6 (-25.7)	TS(4 → 5)	20.8 (20.1)	20.3 (19.7)
	5 → 6	-20.4 (-19.7)	-20.5 (-19.7)	TS(5 → 6)	30.5 (30.0)	30.7 (30.4)
	3a → 8	-8.1 (-9.2)	-10.3 (-11.7)	TS(3a → 8)	0.9 (0.4)	0.6 (0.1)
B	8 → 5	-19.3 (-21.3)	-15.9 (-18.0)	TS(8 → 5)	16.9 (15.4)	18.9 (17.3)
	3a → 9	-23.2 (-23.2)	-21.5 (-22.0)	TS(3a → 9)	17.3 (17.0)	16.9 (16.3)
C	9 → 10	-5.5 (3.1)	-6.6 (2.0)	TS(9 → 10)	12.1 (11.7)	10.8 (10.1)
	10 → 11	-11.5 (-11.1)	-9.2 (-8.6)	TS(10 → 11)	3.5 (3.0)	3.7 (3.0)
	9 → 15	-4.6 (-6.6)	-0.3 (-2.4)	TS(9 → 15)	27.6 (27.7)	26.0 (26.0)
	15 → 16	6.9 (17.4)	-0.3 (9.8)			
A	3a → 3b	X=OCH ₃ 8.1 (8.9)	X=N(CH ₃) ₂ 8.0 (8.4)	TS(3a → 3b)	X=OCH ₃ 14.5 (14.4)	X=N(CH ₃) ₂ 15.2 (15.3)
	3b → 4	-12.4 (-14.3)	-8.6 (-10.6)	TS(3b → 4)	8.3 (7.8)	13.1 (12.4)
	4 → 5	-23.2 (-25.2)	-25.8 (-28.1)	TS(4 → 5)	20.0 (19.4)	16.8 (15.2)
	5 → 6	-21.0 (-20.3)	-21.4 (-19.3)	TS(5 → 6)	29.7 (29.3)	30.4 (30.2)
	3a → 8	-9.2 (-10.2)	-12.7 (-14.1)	TS(3a → 8)	0.6 (0.3)	0.5 (0.1)
B	8 → 5	-18.2 (-20.4)	-13.7 (-16.2)	TS(8 → 5)	18.7 (17.3)	21.2 (19.1)
	3a → 9	-25.1 (-25.1)	-23.2 (-24.0)	TS(3a → 9)	14.9 (14.4)	13.4 (13.0)
C	9 → 10	-5.0 (3.6)	-6.6 (2.0)	TS(9 → 10)	12.9 (13.1)	12.9 (11.5)
	10 → 11	-11.6 (-11.1)	-12.3 (-11.8)	TS(10 → 11)	4.0 (3.4)	3.5 (2.6)
	9 → 15	-4.4 (-6.3)	-0.8 (-3.1)	TS(9 → 15)	27.9 (28.0)	25.3 (24.4)
	15 → 16	7.6 (18.0)	1.8 (11.7)			

[a] For notation of the structures, see Schemes 2 and 4. All energies are given in kcal mol⁻¹.

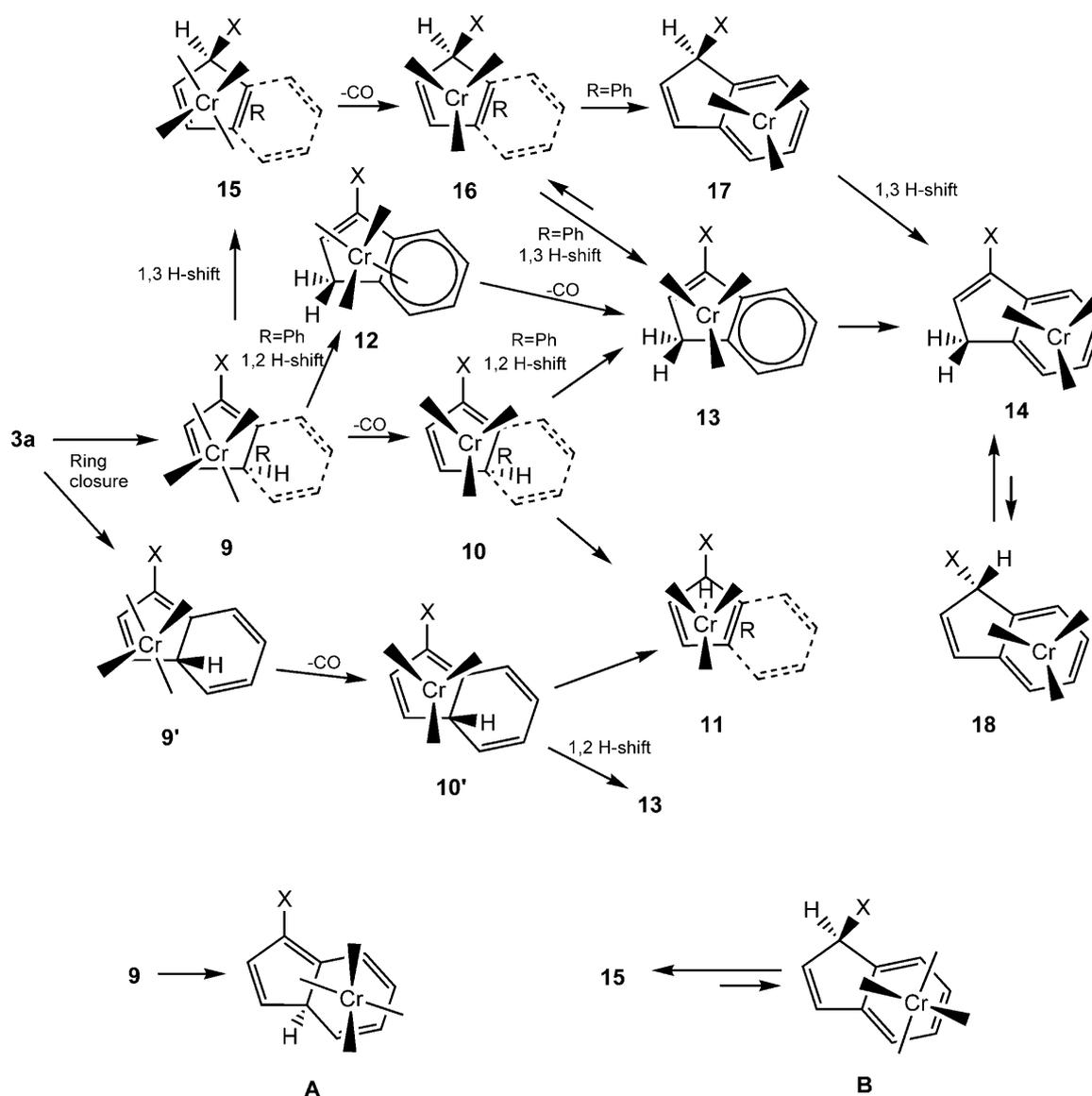
CO can interact concertedly with the terminal C=C and Cr=C π orbitals.^[38] This step is somewhat more favored for alkoxy-carbenes than for aminocarbenes.

As found by GDH,^[39] our results also indicate that phenol formation is more exothermic for hydroxycarbenes than for aminocarbenes. Thus, full transformation from **1**→**6** releases -53.0 (X'=H) and -56.6 kcal mol⁻¹ (X'=CH₃) with [(CO)₅Cr=C(OX')CHCH₂] compared with -50.4 (X'=H) and -53.3 kcal mol⁻¹ (X'=CH₃) with [(CO)₅Cr=C(NX')CHCH₂]. To discuss the most viable reaction mechanism we have to take into account the fact that differences in energy between the TSs and intermediates (and not between TSs and the initial reactants) are decisive in reactions carried out in solvents. In this case, molecular collisions are sufficiently efficient to cool the reactant complex (if this is stable enough to survive for several vibrations), causing it to be in thermal equilibrium with its environment. Thus, looking at the barriers between TSs and intermediates, it was found, first, that all the involved enthalpy barriers are lower than the barrier that has to be surmounted in the initial step of the Dötz reaction (CO dissociation) and, secondly, that the chromahexatriene route is the minimum-energy reaction pathway for the transformation from **3a** to **5** for alkoxyvinyl- and aminovinylcarbenes with the exception of [(CO)₄Cr=C(N(CH₃)₂)CHCH₂]. For instance, for [(CO)₄Cr=C(OH)CHCH₂], the highest barrier in the Dötz reaction mechanism corresponding to the **4**→**5** step is 20.8 kcal mol⁻¹, whereas for the alternative chromahexatriene proposal the highest barrier is just 16.9 kcal mol⁻¹ (**8**→**5**). The energy dif-

ferences between the two mechanisms are smaller for the bulkier X substituents and even the Dötz mechanism becomes the most favorable in the case of the [(CO)₄Cr=C(N(CH₃)₂)CHCH₂] complex. Because the differences in the enthalpy barriers for the two mechanisms for the formation of 6-MRs are relatively small, it is likely that the two mechanisms can be operative in vinylcarbenes with some preference for the chromahexatriene route.

Finally, the third studied route (route C, Scheme 4) corresponds to the formation of the 5-MR product. Some authors have suggested the possibility that indene formation takes place from **3a** through an electrocyclic ring closure to give a chromacyclohexadiene intermediate.^[13,21,27,31] We have been unable to find such an intermediate and all geometry

optimizations carried out starting from a chromacyclohexadiene structure lead to η²-vinylcarbene structures. Thus, according to our results the cyclopentannulation reaction proceeds with the formation of tetracarbonyl η⁴-cyclopentannulated complex **9** from **3a**. By comparing the barriers for the electrocyclization **3a**→**9** for the different X substituents studied, we can see that this process is somewhat favored by bulkier X ligands. This is attributed to the shorter distance between the carbon atoms in **3a** that form the new bond as a result of steric effects. For instance, this distance decreases from 2.139 and 2.128 Å in [(CO)₄Cr=CHCHC(OH)CHCH₂] and [(CO)₄Cr=CHCHC(NH₂)CHCH₂] to 2.124 and 2.115 Å in [(CO)₄Cr=CHCHC(OCH₃)CHCH₂] and [(CO)₄Cr=CHCHC(N(CH₃)₂)CHCH₂], respectively. In addition, bulkier X substituents suffer less steric hindrance when the junction angle is opened in cyclopentannulation reactions (see discussion below). From complex **9**, we have explored the potential energy surface (PES) in detail looking for all intermediates present in the reaction pathways shown in Scheme 4. In the case of vinylcarbenes, depending on the order of carbon monoxide loss and 1,3-hydrogen migration, we found two possible routes: **9**→**10**→**11** or **9**→**15**→**16**. From the data in Table 4, we can see that both initial steps are exergonic, but **9**→**15** is exothermic whereas **9**→**10** is slightly endothermic. On the other hand, migration of the hydrogen to the better stabilized position in **9**→**15** costs more than twice the first CO removal followed by hydrogen migration, so it is clear that the most favorable reaction path in this case is **9**→**10**→**11**. In the (tricyclobenzene-



Scheme 4. Cyclopentannulation reaction pathways studied in this work ($X = \text{OH}, \text{NH}_2, \text{OCH}_3,$ and $\text{N}(\text{CH}_3)_2$; $R = \text{CH}=\text{CH}_2$ and Ph).

mium)cyclopentadiene complex **10** a hydrogen atom is transferred to the chromium atom to form the metal hydride **11** through a small barrier of less than 5 kcal mol^{-1} . Figure 3 displays only the minimum energy path ($9 \rightarrow 10 \rightarrow 11$) found for cyclopentannulation. The transformation $3a \rightarrow 9$ is the step having the largest barrier in route C and it is somewhat favored for aminocarbenes in comparison with alkoxy-carbenes. This is in contrast to the transformation $8 \rightarrow 5$ in the chromahexatriene route, for which the alkoxy-carbenes have slightly smaller barriers. This concurs with the experimental evidence that the ratio of 5-MR formation increases on substitution of an alkoxy group by a better electron donor such as the amino group.^[13,14,27,31]

Because all the routes (A, B, and C) start from the same intermediate **3a**, the product distribution should be explained on the basis of the kinetic parameters of these three routes after the generation of **3a**. The selectivity of this ram-

ification is then determined by the difference in the activation free energy between two reaction routes. From Figure 3, the most energy-demanding step in route B from **3a** for the generation of benzannulated product **6** is the transformation $8 \rightarrow 5$ via $\text{TS}(8 \rightarrow 5)$, which requires activation free energies of 16.9, 18.9, 18.7, and 16.8 kcal mol^{-1} for $X = \text{OH}, \text{NH}_2, \text{OCH}_3,$ and $\text{N}(\text{CH}_3)_2$, respectively. The activation free energies for the generation of the cyclopentannulated product **11** (route C) can be calculated from intermediate **8** to the highest transition state $\text{TS}(3a \rightarrow 9)$ (this is because the generation of **8** from **3a** is very easy, with an energy barrier of nearly 1 kcal mol^{-1} , and **8** is thermodynamically favored over **3a**), and are 25.4, 27.2, 24.1, and 26.1 kcal mol^{-1} , respectively. Intermediate **8** has also to be taken as the reference for route A, leading to activation free energies of 27.2, 37.7, 25.6, 33.8 kcal mol^{-1} in the same order of X substituents, and therefore is energetically less favorable than

route B. Owing to a difference of at least 5 kcal mol^{-1} between the most accessible pathways (routes B and C), we can deduce that 6-MR formation is kinetically preferred over the 5-MR product in these cases. This is in line with experimental observations that vinylcarbenes exclusively give phenols and cyclohexadienones (with few exceptions).^[29,31,65]

Phenylcarbenes: The optimized structures of the intermediates and TSs in the Dötz benzannulation route for $X=OH$ and $R=Ph$ are drawn in Figure 4. Figure 5 shows the energy diagrams for the alkoxyphenyl- and aminophenylcarbenes **1** studied in this work, and Table 5 reports the energy values. In accordance with the results of GDH,^[39] we also find that 6-MR formation is more exothermic for vinylcarbenes than for phenylcarbenes (by about 10 kcal mol^{-1}) because in the former case a new aromatic system is created. Our results show that not only 6-MR but also 5-MR product formation is more exergonic for the vinylcarbenes.

For the Dötz benzannulation mechanism, the main difference with respect to the vinyl substituent is that most of the energy barriers are now significantly lower, which is not unexpected given the fact that Cr–CO bonds in phenylcarbenes are weaker than in vinylcarbenes (Table 3) and the Dötz reaction pathway for 6-MR formation is clearly favored over the chromahexatriene route. At variance with the vinyl case, there is almost no heteroatom effect and, in particular, the barrier for the insertion of CO corresponding to **TS(3b→4)** has similar energy requirements for alkoxy- and aminocarbenes. In addition, this CO insertion is exothermic and exergonic in vinylcarbenes and the other way round for phenylcarbenes. These results indicate that the higher production of cyclopentannulated products in aminocarbenes cannot be attributed to stronger Cr–CO bonds due to the higher π -donor character of the amino groups relative to the alkoxy groups. In steps **4→5** and **5→6** there are remarkable differences between the vinyl and phenyl cases. Both the energy barriers to ring closure, **TS(4→5)**, and tautomerization from the keto to the enol form, **TS(5→6)**, are significantly reduced for the phenyl substituent. In the case of the **4→5** transformation, the reason behind these changes can be found by inspecting the structure of the Wheland intermediate **5**; electrocyclization leads to the formation of a relatively strong agostic interaction between the C–H bond of the carbon atom in the ring junction and the Cr(CO)₃ group that stabilizes intermediate **5** and favors the **4→5** conversion. This agostic interaction is not present in the vinyl analogues. Depending on which side of the phenyl group is attacked by the ketene, below the ring with respect to the tricarbonylchromium tripod (**5a**) or from above (**5b**, see Figure 6), we find two possible intermediates. Our results show that isomer **5a** is lower in energy (4 kcal mol^{-1} on average) than **5b**. In **5b**, the central carbon in the junction of both rings is more pyramidalized and the naphthalenic fragment is less aromatic than in **5a**. Moreover, in **5a** there is the above-mentioned stabilizing agostic interaction. In the case of the keto-to-enol tautomerization, the energy barrier is also lower for the phenylcarbenes than for the vinylcar-

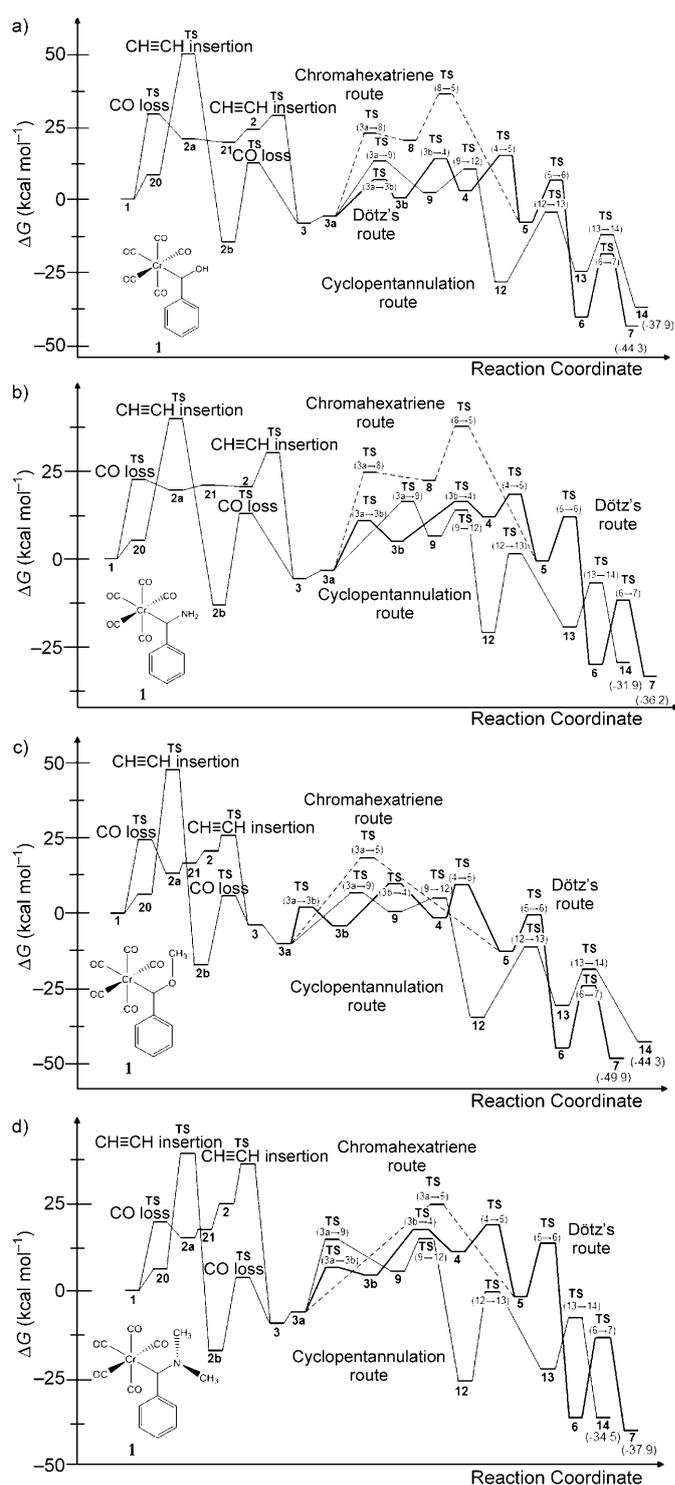


Figure 5. Gibbs free-energy profiles for the Fischer carbenes a) $[(\text{CO})_5\text{Cr}=\text{C}(\text{OH})\text{Ph}]$, b) $[(\text{CO})_5\text{Cr}=\text{C}(\text{NH}_2)\text{Ph}]$, c) $[(\text{CO})_5\text{Cr}=\text{C}(\text{OMe})\text{Ph}]$, and d) $[(\text{CO})_5\text{Cr}=\text{C}(\text{NMe}_2)\text{Ph}]$ for the main studied mechanisms (benzannulation: route A, solid line; route B, dashed line; cyclopentannulation: route C, normal line). Relative energies are given in kcal mol^{-1} .

benes because the hydrogen transfer is assisted by the chromium metal through the formed agostic interaction formed. In addition, the keto-to-enol tautomerization is more ex-

Table 5. Reaction free energies (ΔG_{298}^0) and activation barriers ($\Delta G_{298}^{\ddagger}$) for all steps in the benzannulation (Dötz route, A, and chromahexatriene route, B) and cyclopentannulation (C) reaction pathways calculated at the B3LYP/(Wachters' basis, 6-31G(d,p)) level of theory (enthalpy values, ΔH_{298}^0 and $\Delta H_{298}^{\ddagger}$, are given in parentheses). Results are presented for R=Ph and for the different X substituents studied.^[a]

Route	Step	ΔG_{298}^0 (ΔH_{298}^0)		TS	$\Delta G_{298}^{\ddagger}$ ($\Delta H_{298}^{\ddagger}$)		
		X=OH	X=NH ₂		X=OH	X=NH ₂	
A	3a → 3b	6.5 (7.5)	8.8 (9.0)	TS(3a → 3b)	12.7 (12.0)	15.2 (12.6)	
	3b → 4	2.2 (1.0)	7.4 (6.0)	TS(3b → 4)	13.3 (11.5)	12.3 (11.1)	
	4 → 5	-10.9 (-14.1)	-13.4 (-16.4)	TS(4 → 5)	12.3 (9.6)	7.1 (4.3)	
	5 → 6	-32.8 (-32.3)	-31.8 (-31.4)	TS(5 → 6)	14.6 (14.4)	13.4 (13.0)	
	B	3a → 8	26.4 (25.8)	27.7 (25.7)	TS(3a → 8)	28.8 (27.5)	30.1 (28.4)
		8 → 5	-28.6 (-31.3)	-24.9 (-27.0)	TS(8 → 5)	16.0 (14.6)	16.4 (15.6)
C	3a → 9	8.1 (7.8)	10.4 (9.0)	TS(3a → 9)	19.2 (17.0)	21.2 (18.2)	
	9 → 10	2.9 (12.7)	2.3 (12.2)	TS(9 → 10)	23.3 (24.6)	22.2 (24.1)	
	10 → 13	-30.3 (-31.0)	-30.1 (-30.6)	TS(10 → 13)	14.6 (14.3)	15.0 (14.7)	
	9 → 12	-31.1 (-31.8)	-29.7 (-30.1)	TS(9 → 12)	8.1 (8.5)	8.1 (8.6)	
	12 → 13	3.7 (13.5)	1.9 (11.6)	TS(12 → 13)	24.4 (27.2)	24.2 (26.6)	
	13 → 14	-12.7 (-12.6)	-11.0 (-11.1)	TS(13 → 14)	12.8 (13.6)	13.4 (14.1)	
	14 → 18	9.3 (9.5)	9.3 (9.2)				
	9 → 15	-31.1 (-31.8)	-37.1 (-38.7)	TS(9 → 15)	8.6 (8.2)	6.7 (6.3)	
	15 → 16	8.7 (18.5)	12.1 (22.8)	TS(15 → 16)	31.9 (31.4)	22.9 (24.6)	
	16 → 13	-4.9 (-5.0)	-2.7 (-2.5)	TS(16 → 13)	36.2 (36.1)	38.0 (38.5)	
	16 → 17	-7.7 (-7.7)	-1.3 (-1.2)	TS(16 → 17)	16.6 (17.4)	21.4 (22.4)	
	17 → 14	-9.9 (-9.9)	-12.5 (-12.5)	TS(17 → 14)	33.8 (43.6)	29.7 (29.7)	
	3a → 9'	10.4 (10.6)	12.4 (11.4)				
	9' → 10'	-33.9 (-25.0)	-33.0 (-24.0)	TS(9' → 10')	16.1 (15.7)	16.6 (16.0)	
	10' → 11	11.6 (11.2)	11.9 (11.7)				
	10' → 13	4.3 (3.9)	3.3 (3.2)				
	A	3a → 3b	X=OCH ₃ 6.3 (6.8)	X=N(CH ₃) ₂ 9.8 (9.9)	TS(3a → 3b)	X=OCH ₃ 12.7 (11.9)	X=N(CH ₃) ₂ 12.0 (12.0)
		3b → 4	2.8 (1.8)	6.4 (4.8)	TS(3b → 4)	14.2 (12.2)	12.5 (11.3)
4 → 5		-14.2 (-14.9)	-12.2 (-15.6)	TS(4 → 5)	11.2 (8.5)	7.3 (4.3)	
5 → 6		-34.8 (-32.7)	-32.9 (-32.2)	TS(5 → 6)	12.5 (12.4)	14.5 (14.6)	
B		3a → 5	-6.1 (-6.2)	4.0 (-0.8)	TS(3a → 5)	29.4 (28.0)	29.2 (27.8)
		3a → 9	11.0 (7.1)	10.9 (10.5)	TS(3a → 9)	17.5 (15.2)	19.5 (16.7)
C	9 → 10	-0.2 (12.8)	2.9 (12.2)	TS(9 → 10)	19.3 (24.7)	21.1 (23.0)	
	10 → 13	-31.8 (-32.2)	-29.4 (-30.1)	TS(10 → 13)	13.9 (13.5)	15.6 (15.1)	
	9 → 12	-36.0 (-33.2)	-30.0 (-31.5)	TS(9 → 12)	4.8 (8.8)	8.9 (8.9)	
	12 → 13	4.1 (13.9)	3.5 (13.6)	TS(12 → 13)	23.9 (27.4)	24.3 (27.2)	
	13 → 14	-12.7 (-13.0)	-13.4 (-13.3)	TS(13 → 14)	12.3 (13.2)	13.8 (13.8)	
	14 → 18	9.4 (9.5)	8.1 (7.4)				
	9 → 15	-35.7 (-33.0)	-25.4 (-26.8)	TS(9 → 15)	5.2 (7.2)	7.4 (6.2)	
	15 → 16	9.3 (19.2)	1.3 (10.3)	TS(15 → 16)	47.2 (46.3)	37.4 (36.3)	
	16 → 13	-5.6 (-5.5)	-2.4 (-1.4)	TS(16 → 13)	37.8 (37.9)	37.3 (37.9)	
	16 → 17	-8.7 (-8.5)	-2.8 (-2.4)	TS(16 → 17)	15.8 (16.6)	20.4 (21.5)	
	17 → 14	-9.6 (-10.0)	-13.0 (-12.3)	TS(17 → 14)	34.1 (33.8)	30.6 (31.0)	
	3a → 9'	9.6 (9.4)	9.7 (8.9)				
9' → 10'	-34.0 (-25.2)	-29.3 (-21.4)	TS(9' → 10')	16.6 (16.0)	19.4 (19.4)		
10' → 11	10.9 (10.9)	8.5 (8.9)					
10' → 13	3.5 (3.5)	4.1 (5.1)					

[a] For notation of the structures, see Schemes 2 and 4. All energies are given in kcal mol⁻¹.

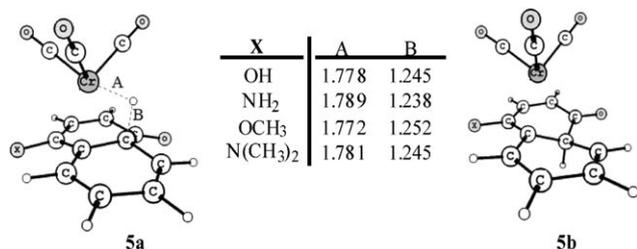


Figure 6. The naphthoquinone derivative prefers the structure **5a** over **5b** because of an agostic stabilizing interaction.

gonic (exothermic) for phenylcarbenes than for vinylcarbenes because in the former case in the final product **6** one recovers aromaticity in two 6-MRs rather than in a single 6-MR as in the case with vinylcarbenes.

From an inspection of the values in Table 5 for the proposed chromahexatriene route B, we can observe dramatic changes on going from vinylcarbenes to phenylcarbenes. Figure 7 provides a resumé of the modifications undergone in this reaction mechanism depending on the kind of Fischer carbene used. As mentioned above, η^1 -vinylcarbene complex **3a** rearranges to η^2 species **8** looking for a first C(carbene)–C(carbonyl) interaction and then carbon monoxide interacts earlier in the transition state and undergoes ring closure when the metal complex is “walking” to its center (the R1 mechanism. Figure 7). However, for the hydroxyphenyl and aminophenyl carbenes, this η^2 conformation is not achieved (the phenyl suffers steric hindrance from the nearest CO ligands when its π system approaches the chromium atom) and a formyl HCO species is formed instead together with a new Cr=C_{phenyl} bond. In the species **8**, the C–H bond of the formyl group forms an agostic interaction with the chromium atom. Thus, the benzannulation proceeds via a formyl complex **8** (not a chromahexatriene intermediate)

and the CO insertion is performed by the aromatic carbon and not the carbene carbon atom as in the case of vinylcarbenes to generate again the Wheland intermediate **5** (**5a**; the R2 mechanism). Intermediate **8** in the case of phenylcarbenes is quite unstable, and for the case of bulkier functional groups (X=OCH₃, N(CH₃)₂) we have been unable to locate this intermediate in the PES. Because intermediate **8** is unstable, the barrier to the transformation of **3a** to **5** corresponds to the energy difference between the highest TS found along the path, **TS(3a**→**5)** or **TS(8**→**5)**, and the energy of **3a**. Thus, route B for phenylcarbenes has

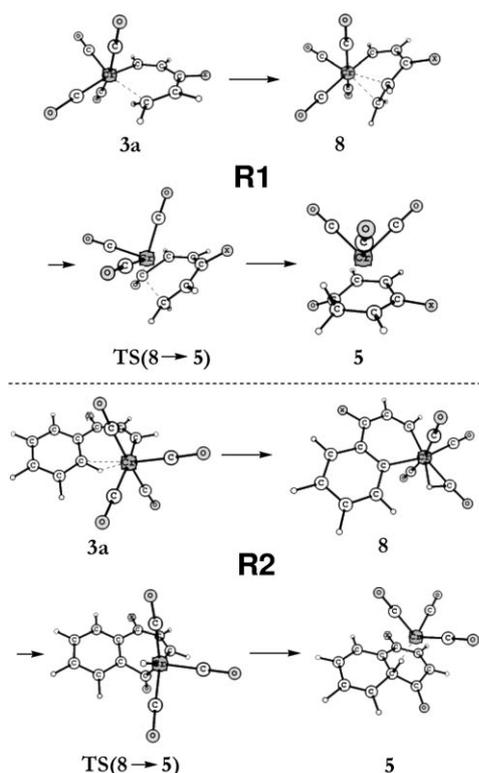


Figure 7. The chromahexatriene pathway changes depending on which substituents are used: R1 is the path followed for all X ligands and R = CH=CH₂ and R2 is followed when X = OH, NH₂, and R = Ph.

barriers of about 30–40 kcal mol⁻¹ and, consequently, the Dötz reaction mechanism is then confirmed as the more feasible proposal for benzannulation in the four phenylcarbenes studied.

Our mechanism for the formation of 5-MRs (see Figure 8 in which we have exemplified the structures involved for the case of [(CO)₄Cr=C(OH)Ph]) differs from some proposals presented in the literature in which the existence of a chromacyclohexadiene intermediate is supposed in the conversion of chromahexatriene **3a** into **9**.^[13,20,33,66] However, as said before, it is not possible to obtain this intermediate and instead **TS(3a→9)**, which directly connects both structures, was located (see Figure 8). This chromacyclohexadiene intermediate is more likely to be present in the [3+2] cycloaddition of imines^[67] due to the more electron-donating character of the imine. From **9**, we have tested several possibilities (see Scheme 4) together with the two routes already explored for vinylcarbenes. In the case of the phenyl derivatives, the hydrogen atom of the phenyl group depicted in Scheme 4 can be positioned on the same or on the opposite face of the ring with respect to the chromium carbonyl fragment when the cyclization is performed. In the latter case, the hydrogen atom can first migrate to a vicinal carbon in **12** and thus proceed to **13** by CO elimination by a route different to the routes **9**→**10** and **9**→**15** already discussed. From **10**, it is not possible now to follow a proton shift to **11** as for vinylcarbenes because of the location of the hydrogen

atom that should be transferred. Instead, the modified route from **10** provides complex **13** through a 1,2-hydrogen shift (see Scheme 4). Moreover, this latter tautomer can also suffer a haptotropic migration of the tricarbonylchromium unit to yield **14** as well as **16** to yield the corresponding **17** haptoisomer. From our calculated energy values, **14** can be regarded as the final product of the reaction because it has a lower energy than all the other discussed intermediates (see Figures S1–S4 in the Supporting Information). On the other hand, we also checked the energies of the isomers of **9** and **10** involved in the route, namely **9'** and **10'**, respectively, as we did previously for **5a** and **5b** (see Figure 6) to discard possible minimum-energy paths leading to species **13** or **11** by tautomerization. Very interestingly, **9** is more stable than **9'** for the less congested X ligands (~4 kcal mol⁻¹), but this is reversed when X becomes bulkier (by a difference of ca. 3 kcal mol⁻¹). The η³ conformation of the Cr(CO)₄ moiety creates a steric hindrance between the hydrogen atom and one equatorial CO in **9'** when X = OH and NH₂, but for bulkier X ligands the repulsion of the methyl group causes rotation of the Cr(CO)₄ group and allows a stabilizing Cr–H agostic interaction that favors the isomer **9'** in this case. Furthermore, **10'** is more stable than **10** by more than 25 kcal mol⁻¹, the reason being the same as that discussed above for **5a** and **5b** in Figure 6 but for a more dense 5-MR instead of 6-MR. Figure 5 shows only reaction pathways for the minimum-energy path to **14**. We also proved haptomigration paths from tetracarbonylchromium species **9** or **15** (and **12**), but whereas we were unable to optimize a hypothetical complex **A** (Scheme 4), from structure **15** we located a haptotropic isomer **B** that was higher in energy by 23 (alkoxycarbenes) to 30 kcal mol⁻¹ (aminocarbenes). This unfavorable Cr(CO)₄ haptotropic rearrangement distorts the benzene ring, which results in a loss of its aromaticity, and therefore we did not include species **A** and **B** in Table 5.

From the energy values of the cyclopentannulation reaction collected in Tables 4 and 5, it can be seen that route C is thermodynamically somewhat more competitive for phenylcarbenes than for vinylcarbenes. Thus, the smallest Gibbs free-energy differences between the most stable 6- and 5-MR products are 5.7 (dimethylaminovinylcarbene) and 3.4 kcal mol⁻¹ (dimethylaminophenylcarbene). At the B3LYP/6-311G++(d,p) level of theory, these energy differences are 1.2 and 0.4 kcal mol⁻¹. Therefore, in the case of the dimethylaminophenylcarbene, differences between 5- and 6-MR formation are insignificant and this is in line with the experimental observation that cyclopentannulation is favored in this case.^[13] Scheme 5 shows the steric hindrance that amino derivatives suffer in the benzannulation reaction of phenylcarbenes. Starting from the carbene skeleton of **3a**, namely **3ax**, one can form the 6-MRs **6'x/6x** or the 5-MRs **14ax**. There is a reduction of 10° in the external junction angle between the two rings for the naphthalenic structure compared with the indenic structure. There is steric repulsion in **6'x** arising from the X' substituents in the amine position that is not present in the vinyl- and alkoxyphenylcarbenes. To avoid this, the amino group rotates around the C–

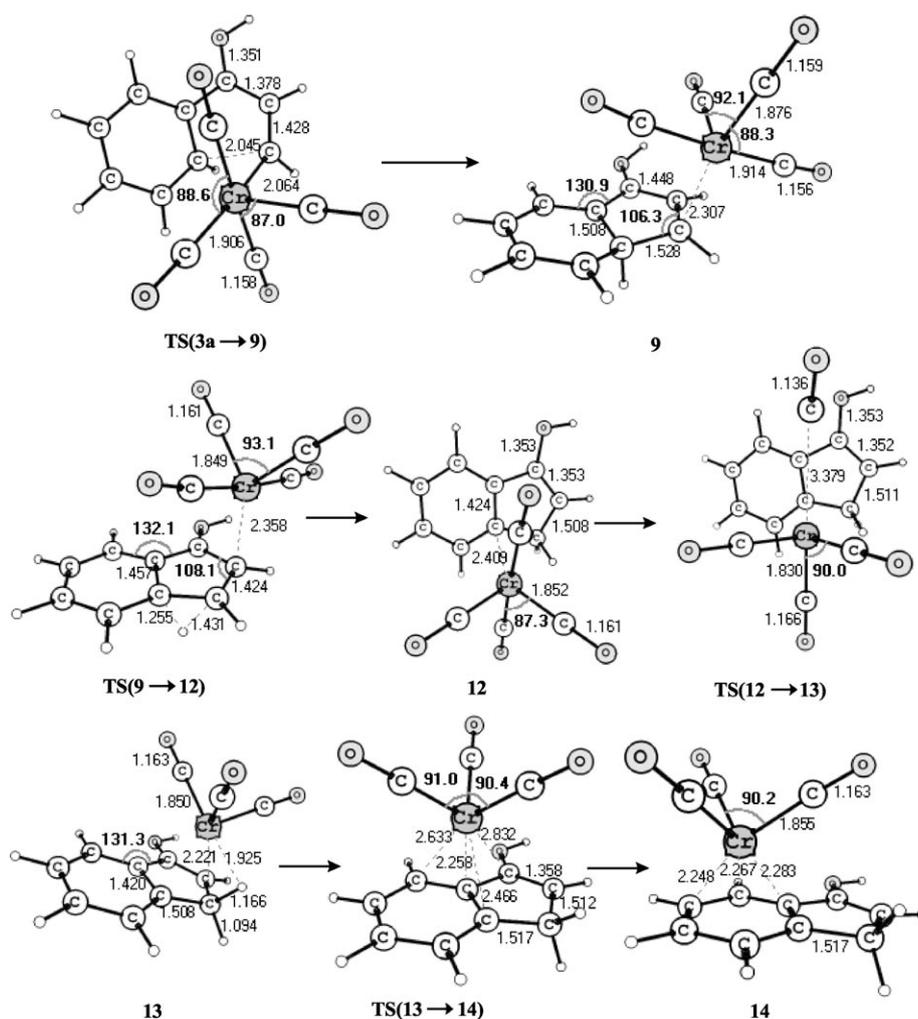
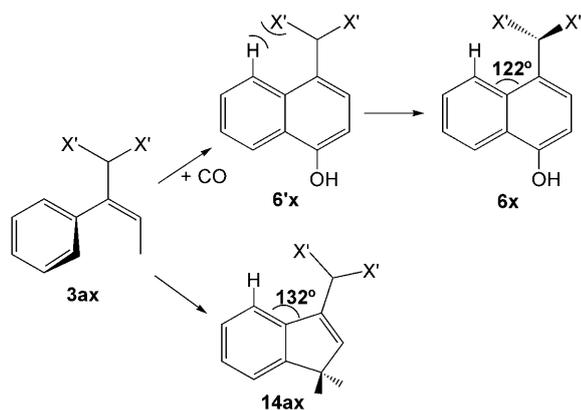


Figure 8. Optimized intermediates and transition-state structures for the most suitable cyclopentannulation routes for the case of X=OH and R=Ph. Distances in Å and angles in degrees.



Scheme 5. Steric hindrance found in the aminocarbenes in the benzannulation product **6x** (Cr(CO)₃ has been omitted for the sake of clarity). The product **6'x** tends to migrate to the intermediate **6x** to avoid X'–H repulsion (X'=H, CH₃).

N bond to yield **6x**. In this conformation, the lone-pair electrons of the nitrogen atom cannot intervene in the π -delo-

calized structure, although it can interact with the nearest hydrogen atom of the nonsubstituted ring. The planarity is not lost when the 5-MR is formed, as in **14ax**, and π delocalization of the nitrogen lone-pair is in this case possible. The destabilization of **6'x/6x** with respect to **14ax** in dialkylaminocarbenes is in part explained by this steric effect. Our results indicate that the cyclopentannulation route **3a**→**9**→**12**→**13**→**14** is the most favored pathway to 5-MR products both from kinetic and thermodynamic points of view for phenylcarbenes.

From Figure 5, it can be seen that the most favored reaction pathway leading to 6-MR products after the generation of **3a** requires activation free energies (calculated as the Gibbs free energy needed to yield **TS(4**→**5)** from **3a**) of 21.0, 23.3, 20.3, and 23.5 kcal mol⁻¹ for X=OH, NH₂, OCH₃, and N(CH₃)₂, respectively. The activation free energies for the generation of the 5-MR products are slightly lower (19.2, 21.1, 17.5, and 19.5 kcal mol⁻¹ in the same order as the barrier to **TS(3a**→**9)**) than those for the 6-

MR products. This could explain why the generation of 6- and 5-MR products is very competitive for the phenylcarbenes. In addition, in the case of dimethylaminophenylcarbene (Figure 5d), route C (cyclopentannulation) is favored over route A (Dötz benzannulation pathway) by the highest difference (4 kcal mol⁻¹), which is in good agreement with the experimental observation that cyclopentannulation is particularly favored in this case.^[13,14,27,31]

As a whole, from a kinetic point of view, our results show that in all cases there are routes that lead to 6- and 5-MR products with energy barriers smaller than the initial CO loss and, therefore, both 6- and 5-MR products are kinetically feasible for all the Fischer carbenes analyzed. Reaction pathways leading to 6-MR products have smaller barriers than those yielding 5-MRs for vinylcarbenes, whereas the opposite holds for phenylcarbenes, in agreement with experimental findings. From a thermodynamic point of view, 6-MR products are generally favored over 5-MR adducts (especially for vinyl- and alkoxy-carbenes), whereas for the dimethylaminophenyl carbene complex the thermodynamic

difference between 6- and 5-MR formation is negligible. Thus, we find that bulky X substituents with high π -donor character reduce the difference in the thermodynamic stability of the 5- and 6-MR products. Our results show that the reaction mechanism is complex with many accessible intermediates and TSs and the kinetic and thermodynamic driving forces are similar for routes A and C with phenylcarbenes, although kinetically route C is somewhat favored. In this situation, minor modifications to the reaction conditions can lead to very different product distributions. For instance, the experimental product distribution^[21] in the case of the Dötz reaction between 3-hexyne and the pentacarbonyl(methoxyphenylcarbene)chromium(0) (0.005 M) in THF at 45 °C is 88% of quinone and less than 1% of indene. When CH₃CN is used as solvent instead of THF, the percentages change to 24 and 14%, respectively.

Finally, for the benzannulated product **6** the phenyl substituent also opens the possibility of exchanging the tricarbonylchromium unit between the rings, as in the case of 5-MRs in the cyclopentannulation reactions discussed above. Figure 9 exemplifies the haptotropic rearrangement for the tricarbonyl(4-naphthohydroquinone)chromium(0) species and Table 6 lists the energetic data computed for both haptoisomers. Recently, we reported on the reaction mechanisms found for the haptotropic migrations in a series of small linear, kinked, fused, and curved polycyclic aromatic hydrocarbons coordinated to a Cr(CO)₃ tripod.^[68,69] We had not yet considered the haptotropic migrations between a functionalized ring (**6**) and a nonsubstituted fused one (**7**) until now. As found experimentally in similar cases,^[70] coordination to the nonsubstituted ring is more favorable than coordination to the substituted ring. In terms of relative energies with respect to complex **6**, the stability of **7** increases marginally on going from OH to OCH₃ substituents and decreases on going from NH₂ to N(CH₃)₂ ligands. The TSs correspond more to η^2 than η^1 structures and are akin to those found for naphthalene.^[68] The TS is structurally closer to the more substituted ring and is not at exactly half the distance between ring centers as expected from Hammond's postulate.^[71] As for the naphthalene case,^[69] no intermediates were located for the transformation **6**→**7**. The barriers of about 20 kcal mol⁻¹ are in perfect agreement with those

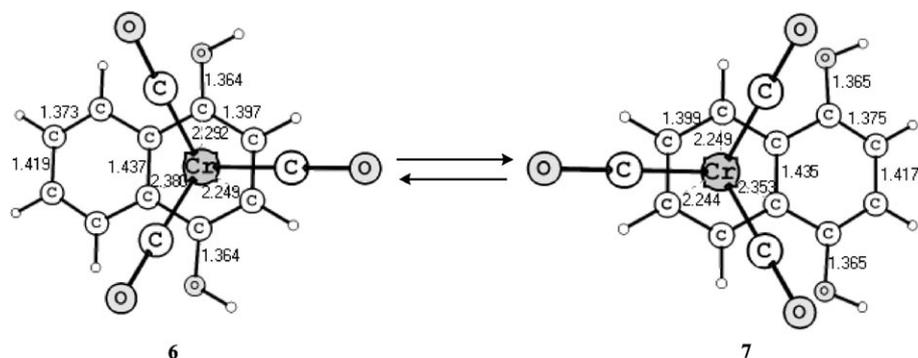
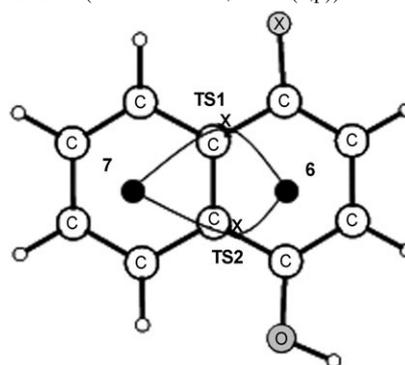


Figure 9. Haptotropic rearrangement reaction for the benzannulated product **6** (for R = Ph and X = OH). Distances are in Å and angles in degrees.

Table 6. Reaction Gibbs free energies and activation barriers for all the haptotropic rearrangements of the naphthol derivative **6** (for R = Ph) calculated at the B3LYP/(Wachters' basis, 6-31G(d,p)) level of theory.



X	OH	NH ₂	OCH ₃	N(CH ₃) ₂
6 → 7	-3.3	-3.6	-3.7	-3.4
TS1 (6 → 7)	21.7	19.7	21.2	21.1
TS2 (6 → 7)	21.7	19.7	21.2	21.7

[a] All energies are given in kcal mol⁻¹.

found experimentally for molecules having the same naphthohydroquinone skeleton but different substituents on the substituted ring.^[70] Although haptotropic migration is only symmetric for 4-naphthohydroquinone, other substitutions at the *para* position do not seem to affect energetically the preference of Cr(CO)₃ to move from one side or the other onto the less substituted ring. A very small difference is noted for the amino side-chain in 4-dimethylamino-1-naphthol in which the organic skeleton adopts the **6x** spatial orientation shown in Scheme 5, but no amino interaction was observed as a possible stabilizing factor. It seems that the barrier for haptomigration is not very sensitive to either electronic or steric effects induced by substituents.

Dötz and Jahr suggested that these haptotropic migrations can be used as novel organometallic molecular switches^[72] in which this rearrangement can be tuned by modification of the reaction conditions or by photoinduction of these chemical species. They also reviewed a variety of benzannulation reactions where this haptotropic migration plays an important role in the synthesis and regioselectivity of organic compounds.^[14] Thus, this last step is one of the most interesting in the Dötz benzannulation reaction because the initial choice/preparation of the Fischer carbene can lead to a regioselective haptoisomer complex in a systematic synthesis. We hope this work will stimulate experimental organic research in the future when considering mechanistic aspects of this fascinating organometallic reaction.

Conclusion

The mechanism of the classic chromium-mediated Dötz benzannulation reaction by acetylene insertion has been examined for some representative Fischer carbenes as well as other competitive reaction mechanisms. The benzannulation and cyclopentannulation reactions are very exothermic and exergonic (30–50 kcal mol⁻¹). Our results indicate that reactions leading to benzannulated and cyclopentannulated products are more exothermic for vinylcarbenes than for phenylcarbenes and also more exothermic for alkoxy-carbenes than for aminocarbenes.

This study has confirmed that the loss of CO in the initial part of the reaction is the rate-limiting step of the reaction. For phenylcarbenes, the dissociative pathway, which corresponds to loss of CO prior to acetylene addition, is the most plausible route to phenylcarbenes **3a** because it has a lower energy barriers than the associative path (first addition of acetylene followed by CO loss). In the case of vinylcarbenes, both the dissociative and associative pathways may be operative because they have similar energy requirements.

Of the two postulated reaction pathways that lead to the 6-MR products studied, we found that the reaction mechanism followed depends on the kind of Fischer carbene used. Thus, the benzannulation of vinylcarbenes is better explained through a chromahexatriene intermediate route, whereas the reaction of phenylcarbenes is best rationalized by the Dötz reaction mechanism. From a thermodynamic point of view, the 6-MR products are generally favored over 5-MR adducts, especially in the case of aminovinylcarbenes and alkoxy-carbenes, whereas for the dimethylaminophenylcarbene complex the difference between 6- and 5-MR formation is negligible. Thus, bulky X substituents with high π -donor character reduce the difference between the thermodynamic stability of 5- and 6-MR products. From a kinetic point of view, our results show that in all cases there are routes operating that lead to the 6- and 5-MR products with smaller energy barriers than the initial CO loss. Starting from complex **3a** as the ramification point, it was found that 6-MR formation is favored in the case of vinylcarbenes, whereas 5-MR production is preferred in the case of phenylcarbenes. It has also been found that the differences between the barriers for CO insertion (**8**→**5** in vinylcarbenes and **3b**→**4** in phenylcarbenes) for the alkoxy and amino groups are small and not critical to explain the differences found in the 5- and 6-MR formation ratio.

Finally, we have discussed the last but not least important step in the Dötz benzannulation reaction of phenylcarbenes, the haptotropic rearrangement. In this reaction, the Cr(CO)₃ tripod migrates from the substituted aromatic ring to the nonsubstituted one.

Computational Methods

We have used the Gaussian 03 computational package^[73] to model the gas-phase reaction mechanisms reported here. We have employed the

hybrid density functional B3LYP^[74] to perform geometry optimizations and compute energy differences. A mixed basis set of 6-31G(d,p)^[75] for the carbon, oxygen, nitrogen, and hydrogen atoms and Wachters' basis set^[76] of the type (14s9p5d3f)/[8s4p3d1f] using the df-expanded contraction scheme (62111111/3312/311/3) for chromium was employed. Table S1 of the Supporting Information shows that the mixed basis set used gives the same quality of results as the 6-31G(d,p) basis set. Stationary points were located by using the Berny algorithm.^[77] For transition states (TSs) in which the potential energy surface (PES) had not yet been explored, we employed the SQTN method.^[78] Frequency calculations indicated that we obtained the correct stationary points characterized by the number of negative eigenvalues of its analytical Hessian matrix (this number is zero for minima and one for any true TS). We also checked that imaginary frequencies exhibit the expected motion and TSs were connected to the corresponding minima by following the minimum energy path through calculations of the intrinsic reaction coordinate (IRC).^[79] We have reported herein, along with enthalpy values, Gibbs free energies at 298 K obtained by including zero-point energies (ZPE), thermal corrections, and entropic terms into the electronic energies for all species. Entropy effects are especially important in the initial part of the reaction in which dissociation processes take place and they become relatively constant for the central part. We considered only closed-shell states (previous calculations on metal carbenes **1** and **3** showed that triplet states are higher in energy than the singlet states by more than 15 kcal mol⁻¹ in all cases). Relativistic effects were ignored in our study because it was demonstrated that they are very small in chromium Fischer carbene complexes.^[53] Finally, solvent effects were not included in this work because the Dötz reaction is carried out in many cases in rather nonpolar solvents such as heptane, benzene, ethers or tetrahydrofuran, although in some cases relatively polar solvents such as acetonitrile have been used.

Acknowledgements

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