Transition metal carbene chemistry. Kinetic studies on the reactions of [methyl(thiomethoxy)carbene]pentacarbonylchromium(0) with morpholine in aqueous acetonitrile—a kinetic evaluation of pK_a^{CH}

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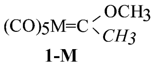
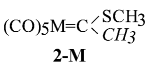
A kinetic study of the aminolysis of [methyl(thiomethoxy)carbene]pentacarbonylchromium(0), $(CO)_5Cr{=}C(CH_3)(SCH_3)$ (**2-Cr**), with morpholine, a secondary amine, in 50% acetonitrile–50% water (v/v) at 25 ° C is reported. The second-order rate constant (k_A in L mol^{-1} s^{-1}) increases with amine concentration, giving a linear dependence with an intercept on the rate axis. The general base-catalyzed nature of the reaction was confirmed by the dependence of the rate on both amine and hydroxide ion concentrations. The mechanism proposed is very similar to those for ester reactions, involving a nucleophilic addition of amine to the substrate to yield a zwitterionic tetrahedral intermediate ($T_A^{\#}$), followed by deprotonation of $T_A^{\#}$ to form T_A^- in a fast step, which, in the third step, is converted to product by a general acid-catalyzed thiomethoxide expulsion. As the carbene itself acts as an acid and only the acid form is active towards aminolysis reactions, the protic equilibrium was evaluated through the aminolysis reaction with morpholine and was found to be in good agreement with the value reported earlier.

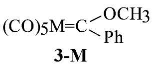
Since their discovery by Fischer and Maasbol[1] in 1964 the group 6 Fischer carbene complexes have been demonstrated to be highly valuable building blocks for the construction of organic molecules.[2] Fischer carbene complexes of the general type **1-M** to **3-M** undergo facile substitution of the XCH_3 group (X = S and O; in general, M = Cr and W, unless otherwise mentioned) with nucleophiles; these reactions are, in general, believed to proceed through a stepwise mechanism with the formation of a tetrahedral intermediate (**4-M**).[3,4]



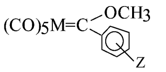
1-M



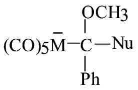
2-M



3-M

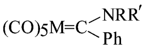


3-M-Z

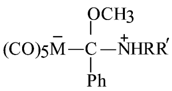


4-M

With NH_3 and with primary and unhindered secondary amines the reaction leads to the corresponding amino carbene complexes (**5-M**),[5–9] but no intermediate has been detected in these aminolysis reactions. Nevertheless, it has been proposed that they proceed through the intermediate **6-M**.[10]

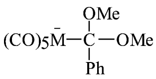


5-M

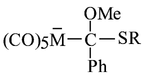


6-M

In the reaction of **3-M** with alkoxide ions[11] and thiolate ions[12] direct detection of intermediates **7-M** and **8-M** was reported.



7-M



8-M

There are only two reports on the kinetics of the aminolysis reaction of **3-Cr** and **3-M-Z** with primary amines[13,14] and none for the thiomethoxy derivatives of these complexes. The objective of the work presented here was to study the kinetics of the aminolysis reactions of [methyl(thiomethoxy)carbene]pentacarbonylchromium(0) (**2-Cr**) with a view to evaluate the pK_a^{CH} of this carbene and to compare it with the reported value.[15]

Experimental

Materials

[Methyl(thiomethoxy)carbene]pentacarbonylchromium(0), $(CO)_5$-$Cr{=}C(CH_3)(SCH_3)$ (**2-Cr**), was synthesized by the method of Lam and Senoff[16] used for the synthesis of phenylmercapto derivatives. Instead of using CH_3SH gas, as used by Fischer and coworkers,[17] CH_3SNa was used in this process. The carbene was characterized by ^1H and ^{13}C NMR in $CDCl_3$ with a 250 MHz Bruker NMR spectrophotometer as follows: ^1H NMR δ 2.65 (s, 3H, CH_3S) and 3.50 (s, 3H, CH_3) and ^{13}C NMR δ 26.87 (CH_3S), 46.03 (CH_3), 216.0 (CO, *cis*), 227.4 (CO, *trans*), 366.9 (C=). These data are very similar to those reported by Fischer *et al.*[17] in $CDCl_3$: ^1H NMR δ 2.68 (s, 3H, CH_3S) and 3.53 (s, 3H, CH_3).

Reagent grade morpholine (Aldrich) was distilled over CaH_2 before use. The spectrum of the reaction product was found to be identical with [methyl(morpholine)carbene]pentacarbonylchromium(0), prepared separately by using the method described by Fischer and Leupold.[8]

pH measurements

The pH in 50% CH_3CN–50% H_2O (v/v) at an ionic strength of 0.10 mol L^{-1} (KCl) and temperature 25 °C (maintained by using a water-jacketed container and flowing water through it from a thermostatic water bath) was determined by using eqn. (1) according to Allen and Tidwell[18] with $pH_{measured}$

referring to the reading of the pH-meter.

$$\mathrm{pH_{actual}} = \mathrm{pH_{measured}} + 0.18 \qquad (1)$$

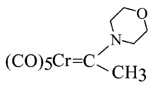
Orion 611 and a digital Systronics-335 (Systronics, India) pH-meters, each equipped with a glass electrode and a reference electrode calibrated with standard aqueous buffers before use were used to measure the pH of the reaction solutions.

Kinetic runs and spectra

A stock solution of the carbene was prepared in anhydrous acetonitrile in which it was found to be fairly stable for several hours. Hewlett Packard 8452A diode array and Shimadzu 335 UV-Vis spectrophotometers were used for generating the time-resolved spectra and for kinetic studies. All kinetic experiments were conducted in 50% CH_3CN–50% H_2O (v/v) under pseudo-first-order conditions with the carbene as the minor component at 25 °C and an ionic strength of 0.10 mol L^{-1} (KCl) by monitoring the disappearance of the substrate at 450 nm. Typical substrate concentrations were $(5.0\text{–}9.0) \times 10^{-5}$ mol L^{-1}. The pseudo-first-order rate constants (k_{obs}, s^{-1}) were obtained by fitting the kinetic traces with a suitable computer-fit program and the results were found to fall within an error limit of ±5% for triplicate runs.

Results

The conversion of **2-Cr** into the amine carbene complex **9-Cr** produces a blue shift in the UV-Vis spectrum (Fig. 1). The identity of the product as **9-Cr** was confirmed by comparison of the spectrum of the solution after the completion of the reaction with the corresponding, independently synthesized amine carbene complex.



9-Cr

The kinetic conditions adopted for the reaction of **2-Cr** with morpholine, a secondary amine, were: [**2-Cr**] = $(5.0\text{–}9.0) \times 10^{-5}$ mol L^{-1}, $[B]_t = 0.007\text{–}0.10$ mol L^{-1} (B = morpholine) and pH 7.68–9.36. In all cases, the observed pseudo-first-order rate constants, k_{obs}, showed a non-linear dependence on [B] (Fig. 2), indicating a change in the order of the reaction from second- or mixed-order to first-order in amine concentration. The corresponding results are summarized in Table 1. [B] was calculated using Henderson's formulation [eqn. (2)]:

$$\mathrm{pH} = \mathrm{p}K_a{}^{BH} + \log[B]/[BH] \qquad (2)$$

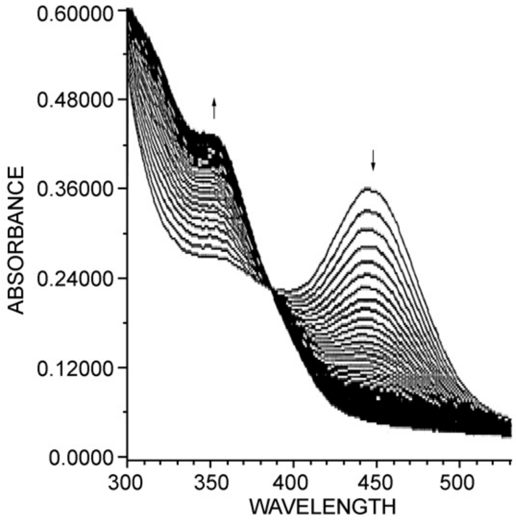


Fig. 1 Time resolved spectra for the reaction between morpholine and **2-Cr** in 50% CH_3CN–50% H_2O. Conditions were: [**2-Cr**] ~6.0×10^{-5} mol L^{-1}, $[\text{morpholine}]_t = 0.02$ M, pH = 8.96, $I = 0.$ mol L^{-1} (KCl) and $T = 25$ °C. The first spectrum was taken after 3 s of mixing and the time intervals are 10 s.

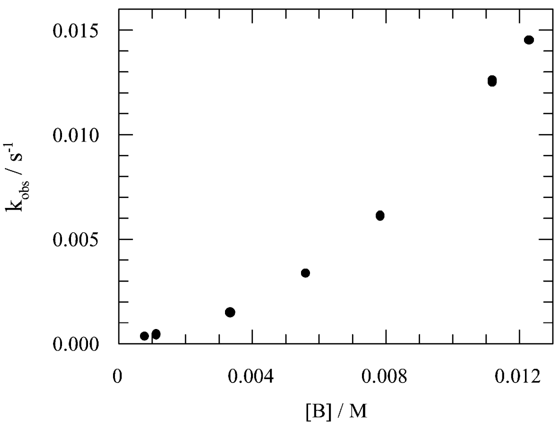


Fig. 2 Plot of k_{obs} *vs.* $[B]_f$ (B = morpholine, free base) for the reactions between morpholine and **2-Cr** in 50% CH_3CN–50% H_2O. Conditions are: [**2-Cr**] ~6.0×10^{-5} mol L^{-1}, pH = 7.80, $I = 0.10$ mol L^{-1} (KCl) and $T = 25$ °C.

For experimental concentrations of morpholine in the range of 0.007–0.10 mol L^{-1}, plots of k_A *vs.* [B] $\{k_A = (k_{obs} - k_h)/[B]\}$ are all straight lines with a positive intercept on the rate axis (an example is shown in Fig. 3). k_h is the auto-hydrolysis rate constant of the carbene and was determined independently from the intercepts of the plots of k_{obs} *vs.* [NMM] (*N*-methylmorpholine) at different pH values (Fig. 4). At higher [B], and particularly at higher pH, the plots are characterized by a rapid initial rise, followed by a leveling off. For convenience, only the linear parts of the plots were considered to evaluate the slope and intercept values that are listed in Table 2.

Discussion

Given the increase in k_A with amine concentration and in analogy with other observations to be published later,[19] it is most likely that general base catalysis is operative here. A mechanism consistent with the above findings can be framed as in Scheme 1.

In Scheme 1, $k_3{}^B$ and $k_3{}^{OH}$ represent the general base-catalyzed paths whereas k_2 is for the uncatalyzed path. Application of the steady-state approximation to $T_A{}^{\#}$ leads to the rate law in eqn. (3):

$$-\frac{d[2\text{-Cr}]}{dt} = \frac{k_1(k_2 + k_3{}^B[B] + k_3{}^{OH}[OH^-])}{k_{-1} + k_2 + k_3{}^B[B] + k_3{}^{OH}[OH^-]}[2\text{-Cr}][B] \qquad (3)$$

The second-order rate constant, $k_A = (k_{obs} - k_h)/[B]$, is given as:

$$k_A = \frac{k_1(k_2 + k_3{}^B[B] + k_3{}^{OH}[OH^-])}{k_{-1} + k_2 + k_3{}^B[B] + k_3{}^{OH}[OH^-]} \qquad (4)$$

which can be rearranged to:

$$k_A = \frac{k_1\{(k_2/k_{-1}) + (k_3{}^B/k_{-1})[B] + (k_3{}^{OH}/k_{-1})[OH^-]\}}{1 + (k_2/k_{-1}) + (k_3{}^B/k_{-1})[B] + (k_3{}^{OH}/k_{-1})[OH^-]} \qquad (5)$$

Under all reaction conditions used in this study the k_2 path for the non-catalyzed conversion of $T_A{}^{\#}$ to products can be assumed to be negligible and eqn. (5) simplifies to: (6)

$$k_A = \frac{k_1\{(k_3{}^B/k_{-1})[B] + (k_3{}^{OH}/k_{-1})[OH^-]\}}{1 + (k_3{}^B/k_{-1})[B] + (k_3{}^{OH}/k_{-1})[OH^-]} \qquad (6)$$

Three special cases may arise, which are considered below.

Table 1 Summary of pseudo-first-order rate constants as a function of morpholine concentration for the reaction of [methyl(thiomethoxy)-carbene]pentacarbonylchromium(0) with morpholine in 50% CH_3CN–50% H_2O (v/v) at different pHs with **[2-Cr]** = ~9.0×10^{-5} mol L^{-1}, $I = 0.10$ mol L^{-1} (KCl) and $T = 25\,°C$

$[B]_t$/mol L^{-1}	pH	$10^3[B]_f{}^a$/ mol L^{-1}	$10^3\ k_{obs}/s^{-1}$	$k_A{}^a$/L $mol^{-1}\ s^{-1}$
0.01	7.68[b]	0.87	0.29	0.19
0.03		2.62	1.19	0.41
0.05		4.36	2.45	0.54
0.07		6.10	3.94	0.63
0.10		8.72	8.15	0.92
0.11		9.59	10.1	1.04
0.007	7.80[c]	0.78	0.31	0.23
0.01		1.12	0.43	0.27
0.03		3.35	1.47	0.40
0.05		5.59	3.36	0.58
0.07		7.83	6.09	0.76
0.10		11.2	12.5	1.10
0.11		12.3	14.5	1.17
0.01	7.86[d]	1.26	0.35	0.29
0.03		3.78	1.92	0.47
0.05		6.30	4.17	0.64
0.07		8.82	7.70	0.86
0.10		12.6	14.6	1.14
0.12		15.2	20.0	1.31
0.007	8.14[e]	1.51	0.51	0.26
0.01		2.16	0.78	0.31
0.03		6.48	4.09	0.61
0.05		10.8	9.70	0.89
0.07		15.1	17.2	1.13
0.10		21.6	31.9	1.47
0.01	8.40[f]	3.34	1.97	0.55
0.02		6.68	5.38	0.79
0.03		10.0	10.7	1.05
0.05		16.7	26.3	1.57
0.07		23.4	45.9	1.96
0.10		33.4	86.1	2.57
0.12		40.1	112	2.80
0.007	8.63[g]	3.22	2.27	0.67
0.01		4.60	3.88	0.82
0.03		13.8	18.9	1.36
0.05		23.0	43.8	1.90
0.07		32.2	76.9	2.38
0.10		46.0	143	3.10
0.007	8.78[h]	3.82	3.09	0.78
0.01		5.46	4.87	0.87
0.03		16.4	24.0	1.46
0.05		27.3	56.5	2.07
0.07		40.9	112	2.73
0.10		54.6	170	3.11
0.12		65.5	252	3.84
0.01	8.83[i]	5.74	5.60	0.95
0.03		17.2	29.2	1.69
0.05		28.7	64.0	2.23
0.07		40.0	115	2.87
0.10		57.4	223	3.89
0.01	9.00[j]	6.66	7.00	1.02
0.02		13.3	17.3	1.29
0.03		26.6	50.7	1.90
0.05		40.0	96.6	2.42
0.07		53.3	150	2.81
0.10		66.6	237	3.56
0.12		79.9	313	3.92
0.01	9.14[k]	7.34	7.56	1.01
0.02		14.7	18.2	1.23
0.03		22.0	30.9	1.40
0.05		36.7	69.1	1.88
0.07		51.4	113	2.19
0.10		73.4	205	2.79
0.007	9.36[l]	5.74	6.49	1.01
0.02		16.4	23.7	1.43
0.03		24.6	40.5	1.64
0.05		41.0	82.1	2.00
0.07		57.4	122	2.28
0.10		82.1	227	2.76
		123	294	2.94

[a] $[B]_f$ indicates the free base concentration, which was calculated by using eqn. (2); k_A was evaluated from: $(k_{obs} - k_h)/[B]_f$. [b] $k_h = 1.17 \times 10^{-4}\ s^{-1}$. [c] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [d] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [e] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [f] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [g] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [h] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [i] $k_h = 1.23 \times 10^{-4}\ s^{-1}$. [j] $k_h = 1.76 \times 10^{-4}\ s^{-1}$. [k] $k_h = 1.74 \times 10{-}4\ s{-}1$. [l] $k_h = 1.74 \times 10{-}4\ s{-}1$.

Case 1. $\{(k_3{}^B/k_{-1})\ [B]) + (k_3{}^{OH}/k_{-1})\ [OH^-])\} \ll 1$. Here eqn. (6) simplifies to eqn. (7):

$$k_A = k_1\{(k_3{}^B/k_{-1})[B] + (k_3{}^{OH}/k_{-1})[OH^-]\} \qquad (7)$$

A general base-catalyzed conversion of $T_A{}^\#$ to product, *i.e.* leaving group (thiomethoxide ion) departure is rate-limiting, and this occurs in particular at low amine and OH^- concentrations where a linear increase in k_A with amine and OH^- concentrations is prevailing.

Case 2. $(k_3{}^B/k_{-1})\ [B]) \gg 1$. In this case eqn. (6) reduces to eqn. (8):

$$k_A = k_1 \qquad (8)$$

and nucleophilic attack on the carbene carbon becomes rate-limiting. Here, k_1 corresponds to the plateau value in the plot of k_A *vs.* [B].

Case 3. $(k_3{}^{OH}/k_{-1})\ [OH^-]) \gg 1$. This is similar to Case 2, where eqn. (6) reduces to eqn. (8) and a plateau is obtainable for a plot of k_A *vs.* $[OH^-]$.

Based on the nature of the dependence of k_A on [B] it is apparent that Case 1 is operative in the present investigation and eqn. (7) is applicable to extract the kinetic parameters.

A plot of k_A *vs.* [B] at a particular pH would yield a straight line giving a slope $k_S = k_1k_3{}^B/k_{-1}$ and an intercept $k_i = k_1(k_3{}^{OH}/k_{-1})[OH^-]$. A plot of k_i *vs.* $[OH^-]$ ($[OH^-]$ was calculated from: $pOH = pK_w - pH$; $pK_w = 15.19$ in 50%

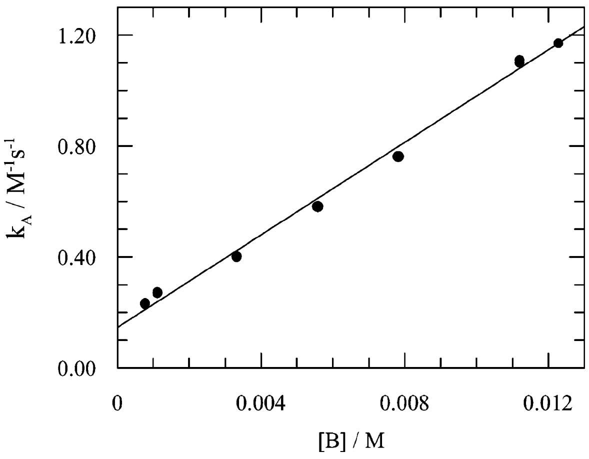


Fig. 3 Plot of k_A (second-order rate constant) *vs.* $[B]_f$ (B = morpholine, free base) for the reaction between morpholine and **2-Cr** in 50% CH_3CN–50% H_2O. Conditions are: **[2-Cr]** ~6.0×10^{-5} mol L^{-1}, pH = 7.80, $I = 0.10$ mol L^{-1} (KCl) and $T = 25\,°C$.

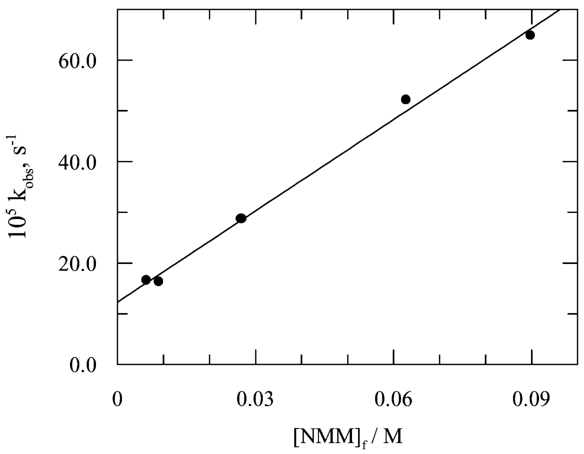
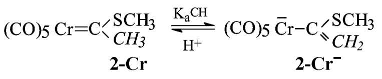


Fig. 4 Plot of k_{obs} *vs.* [NMM] (NMM = *N*-methylmorpholine) for the hydrolysis of **2-Cr** in *N*-methylmorpholine buffer in 50% CH_3CN–50% H_2O (v/v). Conditions are: [**2-Cr**] ~6.0×10^{-5} mol L^{-1}, pH = 8.51, I = 0.10 mol L^{-1} (KCl) and T = 25 °C.

Table 2 Values of the slopes and intercepts obtained from plots of k_A *vs.* $[B]_{free}$ at different pH for the reaction of [methyl(thiometoxy)carbene]pentacabonylchromium(0) with morpholine in 50% CH_3CN–50% H_2O (v/v). Conditions are: [**2-Cr**] = ~9.0×10^{-5} mol L^{-1}, I = 0.10 mol L^{-1} (KCl) and T = 25 °C

pH	k_s/L^2 mol^{-2} s^{-1}	$10 \times k_i$/L mol^{-1} s^{-1}
7.68	92.1 ± 5.3	1.3 ± 0.3
7.80	83.5 ± 2.5	1.5 ± 0.2
7.86	74.3 ± 1.2	1.9 ± 0.1
8.14	60.7 ± 2.0	2.0 ± 0.2
8.40	62.7 ± 2.8	4.2 ± 0.6
8.63	56.6 ± 1.4	5.4 ± 0.4
8.78	48.2 ± 1.8	6.5 ± 0.7
8.83	55.6 ± 1.3	6.8 ± 0.5
9.00	40.1 ± 1.2	7.8 ± 0.6
9.14	26.9 ± 0.7	8.3 ± 0.3
9.36	22.6 ± 1.5	10.3 ± 0.5

CH_3CN–50% H_2O) is a limiting curve of decreasing slope instead of being first-order in $[OH^-]$. Similarly, a plot of k_s *vs.* $[H^+]$ is also a limiting curve of increasing slope instead of being constant. The nature of the dependence of k_s and k_i on the acidity of the medium manifests the involvement of a protic equilibrium [eqn. (9)] of the carbene complex in the experimental pH region (7.68–9.36) and also that the deprotonated species of the complex is unreactive towards morpholine base.


$$(CO)_5\,Cr{=}C\begin{smallmatrix}SCH_3\\ CH_3\end{smallmatrix} \underset{H^+}{\overset{K_a{}^{CH}}{\rightleftharpoons}} (CO)_5\,\bar{C}r{-}C\begin{smallmatrix}SCH_3\\ CH_2\end{smallmatrix} \quad (9)$$

2-Cr **2-Cr⁻**

This is also supported by the occurence of a very rapid initial decrease in absorbance followed by a slower decay. The extent of decay in absorbance (ΔOD) is dependent on the acidity of the medium. With increase in the pH of the medium ΔOD for the faster step increases. This initial decrease in absorbance has been attributed to the deprotonation of the carbene.[15] So considering the protic equilibrium [eqn. (9)] together with Scheme 1, the rate expression (7) ultimately becomes [eqn. (10)]:

$$k_A = k_1\{(k_3{}^B/k_{-1})[B] + (k_3^{OH}/k_{-1})[OH^-]\} \times \left\{\frac{[H^+]}{K_a^{CH} + [H^+]}\right\} \tag{10}$$

giving a slope and intercept of:

$$k_S = k_1(k_3{}^B/k_{-1})\left\{\frac{[H^+]}{K_a^{CH} + [H^+]}\right\} \tag{11}$$

$$k_i = k_1(k_3^{OH}/k_{-1})[OH^-]\left\{\frac{[H^+]}{K_a^{CH} + [H^+]}\right\} \tag{12}$$

$$= k_1(k_3^{OH}/k_{-1})\left\{\frac{K_W}{K_a^{CH} + [H^+]}\right\} \tag{13}$$

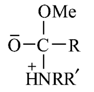
where $K_w = [OH^-] \times [H^+]$.

Eqns. (11) and (13) were solved using the corresponding k_s and k_i values as functions of $[H^+]$ by means of suitable non-linear regression analysis[14,15] and the evaluated values are: $k_1(k_3{}^B)/k_{-1} = (86.3 \pm 4.6)$ L^2 mol^{-2} s^{-1} and $K_a{}^{CH} = (1.27 \pm 0.30) \times 10^{-9}$ L mol^{-1} (p$K_a{}^{CH}$ = 8.90) from eqn. (11) and $k_1(k_3{}^{OH})/k_{-1} = (3.79 \pm 0.16) \times 10^5$ L^2 mol^{-2} s^{-1} and $K_a{}^{CH} = (2.8 \pm 0.20) \times 10^{-9}$ L mol^{-1} (p$K_a{}^{CH}$ = 8.68) from eqn. (13). The ratio is calculated to be $k_3{}^{OH}/k_3{}^A = 4.4 \times 10^3$. As the slope values are more reliable than the intercepts it is reasonable to consider the p$K_a{}^{CH}$ extracted from eqn. (11). There is a reasonable agreement between the evaluated p$K_a{}^{CH}$ (8.90) and the previously reported value for **2-Cr** (9.03),[15] which demonstrates the self-consistency of the proposed mechanism.

The base-catalyzed conversion of the tetrahedral intermediate $T_A{}^{\#}$ to product may occur *via* two possible mechanisms, (i) & (ii) shown in Schemes 2 and 3, respectively.

Comparison of Scheme 2 to Scheme 1 reveals that $k_3{}^A = k_{3P}{}^A$ and $k_3{}^{OH} = k_{3P}{}^{OH}$, while comparison of Scheme 3 to Scheme 1 gives $k_3{}^B = k_3{}^{BH}K_a{}^{\#}/K^{BH}$ and $k_3{}^{OH} = k_3{}^{H_2O}K_a{}^{\#}/K_w$.

Very often the aminolysis of acyl esters and Fischer carbene complexes are compared,[2–4,10] as these reactions typically proceed *via* a tetrahedral intermediate with a rate-limiting deprotonation of the corresponding zwitterion **10**.[20]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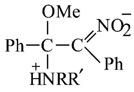
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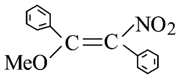
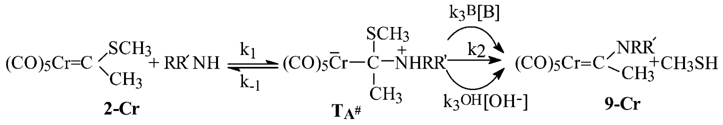

12

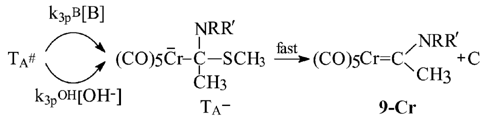
On the contrary, the deprotonation of the corresponding zwitterionic intermediate (**11**) of strongly activated vinylic compounds such as β-methoxy-α-nitrosostilbene (**12**) in its aminolysis reactions is fast and methoxide ion departure is rate-determining.[21]

In the present investigation, mechanism (ii) is assumed to be operative and supports come from the following arguments. (a) It is well known that the proton transfer reaction of acids, except carbon acids, is diffusion controlled. So $k_{3P}{}^{OH}$ refers to an essentially diffusion-controlled proton transfer rate constant (~10^{10} L mol^{-1} s^{-1})[22] and should be independent of amine:

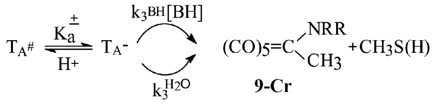
$$k_{3P}{}^{OH}/k_{3P}{}^B = k_3{}^{OH}/k_3{}^B \tag{14}$$



Scheme 1



Scheme 2 Rate-limiting deprotonation of $T_A^{\#}$ followed by rapid leaving group expulsion



Scheme 3 Proton transfer in a rapid pre-equilibrium followed by general acid-catalyzed leaving group departure.

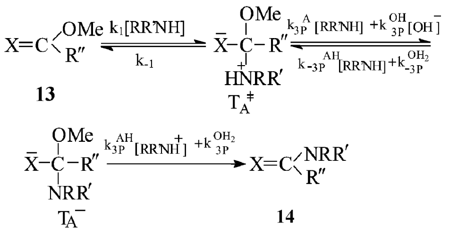
Similarly, k_{3P}^{B} should also be independent of amine. The pK_a of $T_A^{\#}$ is likely to be somewhat lower than the pK_a of the respective amine, which would make the proton transfer from $T_A^{\#}$ to amine thermodynamically favorable with a rate constant close to $4–20 \times 10^8$ L mol^{-1} s^{-1}.[22] Hence the term k_3^{OH}/k_3^{B} should be independent of amine and have values on the order of 5–25. But the experimental value of k_3^{OH}/k_3^{B} (4.4×10^3 L mol^{-1} s^{-1}) is much higher than the value expected on the basis of mechanism (i), Scheme 2.

(b) In the reaction of **3-Cr**[13] and $(CO)_5M = C(SCH_3)(CH_3)$ (**2-M**)[23] with several primary amines it was observed that the ratio k_3^{OH}/k_3^{B} increases strongly with decreasing basicity of the amine and is easily accounted for in terms of mechanism (ii), which follows relationship (15) in which the term K_a^{AH} is involved. On the basis of these observations it is imperative that the reaction of morpholine with the title complex follows the mechanism (ii) where rapid proton transfer from $T_A^{\#}$, followed by rate-limiting methoxide ion expulsion, takes place.

$$\frac{k_3^{OH}}{k_3^{B}} = \frac{k_3^{H_2O}K_a^{BH}}{k_3^{BH}K_W} \qquad (15)$$

If this is the case, then why in their reactions with amines do Fischer carbenes react *via* mechanism (ii) whereas acyl esters follow mechanism (i)? This can be illustrated by considering the general reactions shown in Scheme 4 for the aminolysis reactions.

Two different situations can be considered: (a) when $k_{-1} \gg k_{3P}^{B}[RR'NH] + k_{3P}^{OH}[OH^-]$ and $k_3^{H_2O} \gg k_{-3P}^{BH}[RR'NH_2^+] + k_{-3P}^{H_2O}$, the proton transfer is rate-limiting, and (b) when $k_3^{BH}[RR'NH_2^+] + k_3^{H_2O} \ll k_{-3P}^{BH}[RR'NH_2^+] + k_{-3P}^{H_2O}$, the leaving group departure is rate-determining. Since the proton transfer rate constants should be quite similar in both reactions, the main reason for this difference should be associated with the smaller k_{-1}, k_3^{AH} and $k_3^{H_2O}$ for the Fischer carbene complexes,[24] which can be associated with the greater stability of the $T_A^{\#}$ and T_A^- derived from the carbenes, due to a more effective delocalization of the negative charge onto the $M(CO)_5$ moiety compared to oxygen. This is commonly observed in reactions that lead to delocalized or resonance-stabilized ions. There is evidence of such delocalization in the hydrido transition metal complexes.[25] If this is the case, vinylic substrates such as **12** with X = $C(NO_2)Ph$ would constitute a better analogy for the carbene complexes than acyl esters, since here the negative charge in $T_A^{\#}$ and T_A^- is strongly delocalized onto the NO_2^- group. This leads to a greater stability of the intermediates and the k_{-1}, k_3^{BH} and $k_3^{OH_2}$ steps become relatively slow. Another measure for the differences in stabilizing power is the much higher acidity of **2-Cr** (pK_a = 8.90)[15] compared to ethyl acetate (pK_a = 24.5).[26]



Scheme 4 X = O, acyl esters; and X = $(CO)_5M$, Fischer carbenes

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