Kinetics and Mechanism for the Formation of Phenylhydrazone from Benzaldehydes, Naphthaldehydes, and Formyl-1,6-methano[10]annulenes

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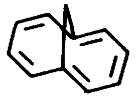
Formation of phenylhydrazone from benzaldehyde, 4-chlorobenzaldehyde, 1-naphthaldehyde, 2-naphthaldehyde, 2-formyl-1,6-methano[10]annulene, and 3-formyl-1,6-methano[10]annulene in 50% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.20M occurs in two steps, (i) the formation of an aminomethanol intermediate and (ii) the dehydration of the aminomethanol to give the products of reaction. Formation of the aminomethanol intermediate is the rate-determining step below pH 5—6 and dehydration of the aminomethanol is the rate-determining step above pH 5—6. Both the reactions are subject to hydronium ion catalysis. The values of the catalytic constants are very similar with all the aldehydes. Formation of the aminomethanol is subject to general acid catalysis by carboxylic acids. The α Brønsted exponents for catalysis of the intermediate formation reaction for the formyl-1,6-methano[10]annulenes are higher than those for the benzaldehydes and smaller than those for the naphthaldehydes. Comparison of the general behaviour of the formyl-1,6-methano[10]annulenes with the benzaldehydes and naphthaldehydes provides strong evidence of the aromatic character of 1,6-methano[10]annulene ring.

Aromaticity is a subject of considerable chemical interest.[1-4] The oldest definition of aromatic character states that aromatic molecules are unsaturated but are nevertheless chemically distinct from alkenes, *e.g.* alkenes readily add molecular bromine whereas aromatic compounds react with molecular bromine to give substitution products, with retention of the unsaturated structure.

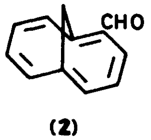
Attempts to quantify and more closely define aromatic character have intensified in recent years, based for instance on the measurement of bond lengths,[5,6] the determination of resonance energies,[7,8] and chemical shifts in ^{1}H and ^{13}C n.m.r. spectroscopy.[9,10]

The first synthesis of a bridged annulene, 1,6-methano[10]annulene (**1**), was reported by E. Vogel *et al.*,[11] who were able to demonstrate the aromatic character of this compound by n.m.r. and u.v. spectroscopy, and by electrophilic aromatic substitution reactions.[11]

We now report the formation of phenylhydrazones from benzaldehydes, naphthaldehydes and 2- and 3-formyl-1,6-methano[10]annulenes (**2**) and (**3**) respectively.



(**1**)



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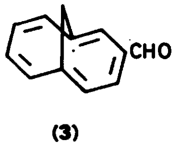

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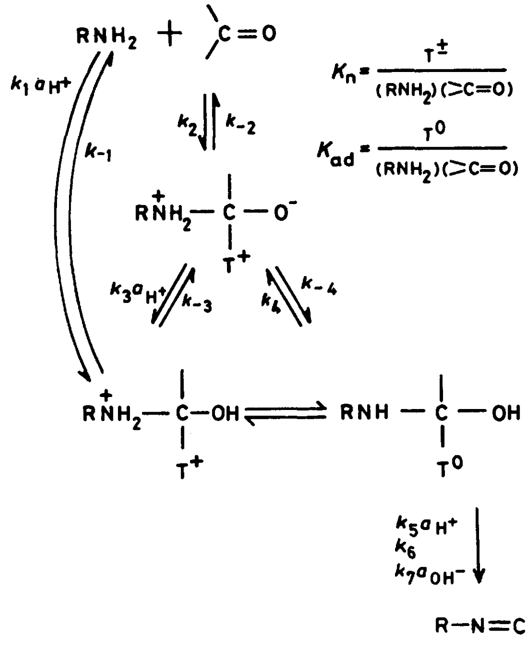

Scheme.

The addition of nitrogen nucleophilic reagents to benzaldehydes occurs in two general stages: (i) formation of an aminomethanol[‡] intermediate; (ii) subsequent dehydration of the aminomethanol to give the imine.[12,13] Formation of the aminomethanol occurs by at least three separates routes:[14-17]

(i) the concerted addition of amine and protonation of the carbonyl oxygen atom ($k_1a_{\mathrm{H}^+}$);

(ii) a stepwise route that involves a zwitterion intermediate, formed by the addition of amine to the carbonyl group, and its subsequent trapping by proton transfer (k_2 followed by $k_3K_na_{\mathrm{H}^+}$);

(iii) a mechanism that involves preassociation of the reagents with acid acting as catalyst.[§]

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[‡] Also known as carbinolamines.

[§] The Scheme is taken from ref. 15 and does not include the preassociation mechanism.[16] The formulation provided is adequate to account for all results presented herein.

Dehydration of the aminomethanol occurs *via* acid-catalysed, pH independent, and base-catalysed pathways ($k_5a_{\mathrm{H}^+}$, k_6, $k_7a_{\mathrm{OH}^-}$).[18]

Aliphatic aldehydes are much more reactive than benzaldehydes. It was not possible to study the kinetics of the reaction of acetaldehyde and phenylhydrazine but the kinetics could be determined upon reaction with urea, a very unreactive nucleophilic reagent.[19]

Similarities in the behaviour between the formyl-1,6-methano[10]annulenes and the benzaldehydes and naphthaldehydes provides strong evidence for the aromatic character of the 1,6-methano[10]annulene ring.

Experimental

Materials.—2-Formyl-1,6-methano[10]annulene and 3-formyl-1,6-methano[10]annulene were synthesized in the laboratories of Professor E. Vogel at the Institute of Organic Chemistry of the University of Cologne, West Germany. All other reagents employed were obtained commercially and, with the exception of reagent grade inorganic salts, were either redistilled or recrystallized before use. Solutions of phenylhydrazine were prepared just prior to use. Solutions of carboxylic acids in 50% aqueous ethanol (v/v) were prepared just prior to use to avoid esterification.

Kinetics.—Reaction of 4-chlorobenzaldehyde with phenylhydrazine in 20% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.50M and the reactions of the benzaldehydes, naphthaldehydes, and formyl-1,6-methano[10]annulenes with phenylhydrazine in 50% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.20M (except in strongly acidic solutions) were followed spectrophotometrically employing a Zeiss PMQ II spectrophotometer equipped with a thermostatted cell holder, under pseudo-first-order conditions, using procedures described previously.[20] The wavelengths and initial aldehyde concentrations used for the kinetic experiments are given in Table 1.

Corrections for general acid catalysis by buffers and phenylhydrazinium ion were made by extrapolation to zero for plots of k_2, the second-order constant in terms of amine free base, against buffer or amine concentration.

In the case where the dehydration reaction made a significant contribution to the overall rate, correction for general acid catalysis was made using $k_{\mathrm{ad.}}$, the second-order rate constant for the formation of aminomethanol, since only this reaction is subject to buffer catalysis under the present experimental conditions; $k^0_{\mathrm{obs.}}$, the second-order rate constant at zero buffer concentration, was then calculated from $k^0_{\mathrm{ad.}}$ as previously described.[21]

pK_a *Determination.*—The pK_a of phenylhydrazinium ion (4.91 ± 0.02) was measured at 25.0 °C in 50% aqueous ethanol (v/v) and an ionic strength of 0.20M maintained with KCl, by careful partial neutralization of nine samples of the hydrochloride to different extents with known amounts of standard sodium hydroxide solution. The pK_a of cyanoacetic acid (2.83 ± 0.04), chloroacetic acid (3.29 ± 0.02), formic acid (4.03 ± 0.02), β-bromopropionic acid (4.71 ± 0.02), and acetic acid (5.22 ± 0.03) were measured at 25.0 °C in 50% aqueous ethanol (v/v) and ionic strength 0.20M maintained with KCl, by careful partial neutralization of nine samples of the acids to different extents with known amounts of standard sodium hydroxide solution. All the experiments were made in triplicate. The pH values of these solutions were measured with a Corning Model 12 pH meter, equipped with a glass electrode.

Table 1. Experimental conditions for reactions of phenylhydrazine with several aromatic aldehydes in 50% aqueous ethanol (v/v) 25.0 °C, ionic strength 0.2M

Aldehyde	λ (nm)	Initial concn. (M)
Benzaldehyde	340	3.33×10^{-5}
4-Chlorobenzaldehyde	348	3.33×10^{-5}
1-Naphthaldehyde	369	3.75×10^{-5}
2-Naphthaldehyde	353	3.33×10^{-5}
2-Formyl-1,6-methano[10]annulene	390	4.00×10^{-5}
3-Formyl-1,6-methano[10]annulene	375	4.00×10^{-5}

The glass electrode was calibrated with two buffer solutions comprising 50% aqueous ethanol (v/v), ionic strength (0.20M; KCl) and different concentrations of acid, *i.e.* 0.0100M and 0.0010M-HCl the pH of which was taken as 2.00 and 3.00, respectively. Under such conditions the measured pH refers to hydronium ion concentration rather than to hydronium ion activities. The pK_a was obtained from measured values of pH employing the Henderson–Hasselbach equation with the corrections proposed by Serjeant.[21]

Results

Recently we have studied the kinetics and mechanism of phenylhydrazone formation from several aldehydes and ketones in 20% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.50M.[17–19] In this work we present an extension of the pH–rate profile for phenylhydrazone formation from 4-chlorobenzaldehyde in 20% aqueous ethanol, at 25.0 °C and ionic strength 0.50M to the H_0 region (Figure 1). The pH–rate profile shows a break in the pH range 5—6, characteristic of a transition from the rate-determining step of aminomethanol formation at acidic pH values to aminomethanol dehydration at less acidic values. The pH–rate profile exhibits a second break under more acidic conditions. The second break presumably reflects a transition from the acid-catalysed stepwise formation of the aminomethanol, $k_3K_na_H$, under conditions less acid than pH 1—2, to uncatalysed addition of amine, k_2, between *ca.* pH 0—1 and, finally to the concerted addition mechanism k_1a_H, under even more acidic conditions.[14,15] Rate constants are given in Table 2.

Steady-state treatment of the Scheme yields the following equation for product formation in the region of rate-determining aminomethanol formation.[15] The equation for the rate-determining aminomethanol dehydration is:

$$k^0_{\mathrm{obs.}} = \frac{k^0_{\mathrm{ad.}}\, K_{\mathrm{ad.}}\, k_5a_{\mathrm{H}^+}}{k^0_{\mathrm{ad.}} + K_{\mathrm{ad.}}\, k_5a_{\mathrm{H}^+}} \qquad (1)$$

$$k^0_{\mathrm{ad.}} = \frac{k_1a_{\mathrm{H}^+} + k_2(K_nk_4 + K_nk_3a_{\mathrm{H}^+})}{k_2 + K_nk_4 + K_nk_3a_{\mathrm{H}^+}} \qquad (2)$$

$$k^0_{\mathrm{deh.}} = K_{\mathrm{ad}}k_5a_{\mathrm{H}} \qquad (3)$$

Table 2. Rate and equilibrium constants for phenylhydrazone formation from 4-chlorobenzaldehyde in 20% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.50M[a]

$k_1 = 7.6 \times 10^3\ \mathrm{M}^{-2}\ \mathrm{s}^{-1}$

$k_2 = 5.0 \times 10^2\ \mathrm{s}^{-1}$

$K_nk_3 = 2.1 \times 10^4\ \mathrm{M}^{-2}\ \mathrm{s}^{-1}$

$K_nk_4 = 1.7 \times 10^1\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$

$K_{\mathrm{ad.}}k_5 = 5.0 \times 10^6\ \mathrm{M}^{-2}\ \mathrm{s}^{-1}$

[a] Rate and equilibrium constants are defined in the Scheme.

The solid line shown in Figure 1 had been calculated employing equations (1) and (2) together with the rate constants in Table 2. The fit of experimental points to the theoretical line is acceptable.

Since the phenylhydrazones formed from the naphthaldehydes and the formyl-1,6-methano[10]annulenes are insoluble in 20% aqueous ethanol the kinetics of their formation were studied in 50% aqueous ethanol.

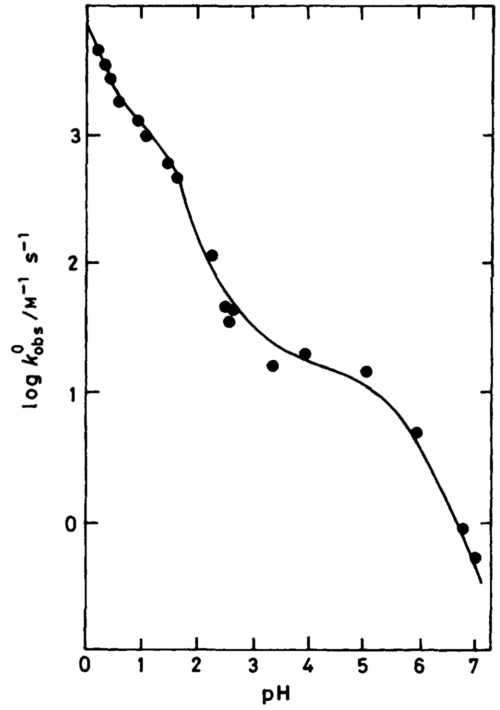

Figure 1. Plots of the logarithms of the second-order rate constants, $k^0_{obs.}$, corrected for aminomethanol accumulation where necessary and extrapolated to zero buffer concentration, for 4-chlorobenzaldehyde phenylhydrazone formation plotted as a function of pH or H_0.

All measurements were made in 20% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.50M. The solid line is the theoretical one derived from equations (1) and (2), and rate constants collected in Table 2. At the highest concentration of acid employed, values of H_0 in 20% aqueous ethanol were taken from M. Sadek, *Suom. Kemistil*, 1966, **39**, 225, and G. Braude, *J. Chem. Soc.*, 1971, 1948.

The observed pH–rate profiles for phenylhdrazone formation from benzaldehyde, 4-chlorobenzaldehyde, 1-naphthaldehyde, 2-naphthaldehyde, 2-formyl-1,6-methano[10]annulene, and 3-formyl-1,6-methano[10]annulene are consistent with a simple two-step mechanism for carbonyl additions of this type (Figure 2).[14,15] At low pH there is a region of slope 1.0 corresponding to hydronium ion catalysis of the formation of the aminomethanol intermediate ($k_1a_{H^+}$), and at intermediate pH, a region where the slope approaches zero, corresponding to uncatalysed formation of the aminomethanol (K_nk_4). A change in the rate-determining step gives a negative break in the pH–rate profile between pH 5—6, and at higher pH values dehydration of the aminomethanol intermediate is the rate-determining step ($k_5a_{H^+}$). Rate constants for k_1, K_nk_4, and $K_{ad}k_5$ are given in Table 3.

Steady-state treatment of the Scheme gives the following equation for product formation in the region of the rate-determining aminomethanol formation:

$$k^0_{ad.} = k_1a_{H^+} + K_nk_4 \qquad (4)$$

The solid lines shown in Figure 2 have been calculated employing the rate expression in equations (1) and (4) together with rate constants in Table 3. The fit of experimental points to the theoretical lines is acceptable.

Under conditions in which formation of the aminomethanol intermediate is rate-determining, second-order rate constants for phenylhydrazone formation from each of the aldehydes are sensitive functions of the nature and concentration of the carboxylic acid–carboxylate buffer employed to maintain constant pH. Measurements of the catalytic effect as a function of the ratio of acidic and basic forms of the buffer established that the catalysis, within experimental error, is of the general acid type (see Table 4). That is, slopes of the plots of the second-order rate constants against the concentration of the acidic component of the buffer yield straight lines with equal slopes regardless of the buffer composition. Catalytic constants were obtained directly from these slopes (Table 5). These results are consistent with previously established catalytic patterns for closely related reactions.[14,19] In addition, catalysis by the

Table 3. Kinetic constants for the reaction of phenylhydrazine with several aldehydes in aqueous ethanol 50% (v/v) at 25.0 °C and ionic strength 0.20M

Aldehyde	k_1/ M^{-2} s^{-1}	K_nk_4/ M^{-1} s^{-1}	$K_{ad}k_5$/ M^{-2} s^{-1}
Benzaldehyde	2.0×10^3	2.6×10^0	2.6×10^6
4-Chlorobenzaldehyde	2.4×10^3	3.4×10^0	2.1×10^6
1-Naphthaldehyde	1.1×10^3	7.0×10^{-1}	9.0×10^5
2-Naphthaldehyde	1.5×10^3	1.1×10^0	1.0×10^6
2-Formyl-1,6-methano[10]annulene	5.2×10^2	2.9×10^{-1}	7.8×10^5
3-Formyl-1,6-methano[10]annulene	1.1×10^3	3.0×10^{-1}	2.0×10^5

Table 4. Catalytic constants calculated for chloroacetic acid for the reaction of phenylhydrazine with benzaldehyde[a]

Catalyst	% Base	pK'_a	pH	Concn. (M)	Compensating electrolyte	$k_{cat.}$/ M^{-2} s^{-1}
$ClCH_2CO_2H$	80	3.29	2.70	0.025—0.125	KCl	3.8×10^2
$ClCH_2CO_2H$	50	3.29	3.26	0.025—0.125	KCl	3.9×10^2
$ClCH_2CO_2H$	20	3.29	3.88	0.025—0.125	KCl	3.5×10^2
$ClCH_2CO_2H$	50	3.29	3.20	0.025—0.125	NaBr	4.0×10^2
$ClCH_2CO_2H$	50	3.29	3.21	0.025—0.125	$NaNO_3$	4.0×10^2

[a] In the presence of chloroacetic acid–chloroacetate buffers in 50% ethanol (v/v) at 25.0 °C, and ionic strength 0.20M maintained with several compensating electrolytes.

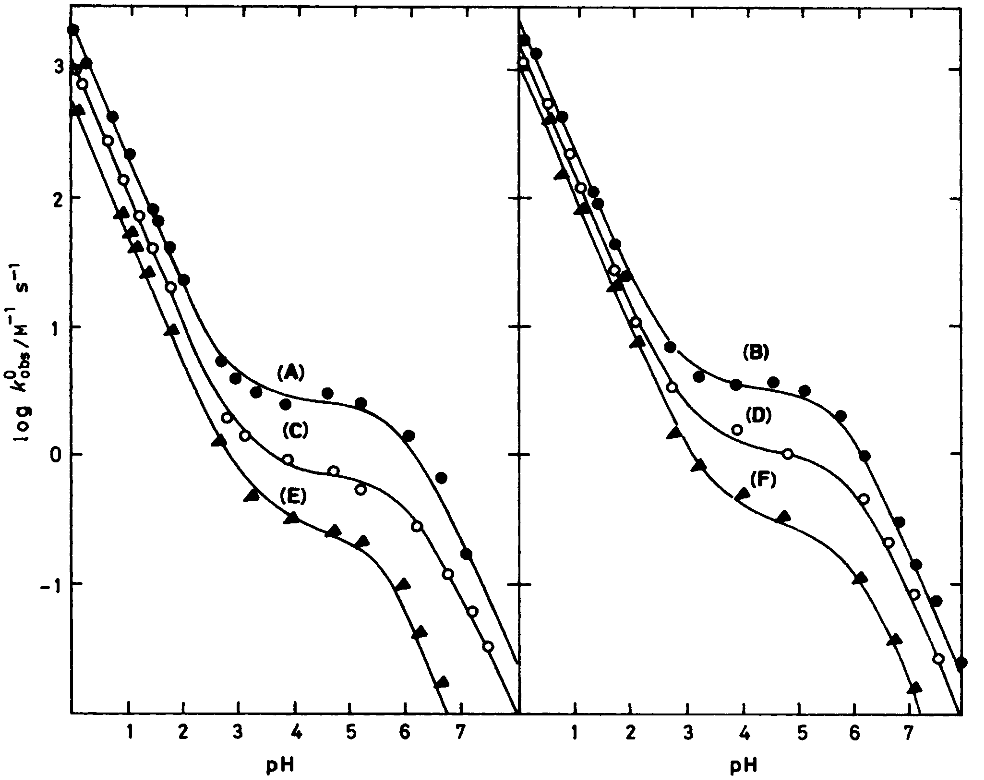

Figure 2. Plots of the logarithms of the second-order rate constants, $k^0_{obs.}$, corrected for aminomethanol accumulation where necessary and extrapolated to zero buffer concentration, for the reaction of phenylhydrazine and benzaldehyde (**A**), 4-chlorobenzaldehyde (**B**), 1-naphthaldehyde (**C**), 2-naphthaldehyde (**D**), 2-formyl-1,6-methano[10]annulene (**E**), and 3-formyl-1,6-methano[10]annulene (**F**).

All measurements were made in 50% aqueous ethanol (v/v) at 25.0 °C and ionic strength 0.20M. The solid lines in each profile are theoretical derived from equations (1) and (4), and the rate constants in Table 3. At the highest concentration of acid employed, values of H_0 in 50% aqueous ethanol were taken from P. Vetesnik, K. Rothschein, J. Socha, and M. Večeřa, *Collect. Czech. Chem. Commun.*, 1969, **34**, 1087.

conjugate acid of phenylhydrazine was evident from the fact that first-order rate constants below pH 5 increased more rapidly than the concentration of phenylhydrazine. Plots of second-order rate constants against the concentration of the conjugate acid of phenylhydrazine yields a catalytic constant for this acid (Table 5).

The observed rate acceleration by carboxylic acid–carboxylate buffers represents true catalysis and not a specific salt effect since plots of second-order rate constants against the concentration of the acid component of the buffer yield straight lines with equal slopes in the presence of different compensating electrolytes (Table 4).[22]

Correlation of the catalytic constants of the carboxylic acids for the formation of phenylhydrazone, in Brønsted plots, by least-square analysis gives the following values for α: benzaldehyde, 0.26; 4-chlorobenzaldehyde, 0.25; 1-naphthaldehyde, 0.62; 2-naphthaldehyde, 0.62; 2-formyl-1,6-methano[10]annulene, 0.32; and 3-formyl-1,6-methano[10]annulene, 0.44.

Dehydration of the intermediate aminomethanol is the rate-determining step above pH 5—6. Determination of an equilibrium constant for the formation of the aminomethanols by spectrophotometric analysis is difficult due to the strong absorption of the aldehydes. However, with each of the aldehydes, the reaction is first-order in phenylhydrazine concentration over the concentration range of 2.0×10^3—1.0×10^{-2}M. Thus, all kinetic studies above pH 5 have been made employing phenylhydrazine concentrations lower than 1.0×10^{-2}M; second-order rate constants could therefore be determined directly from observed rate constants and the concentration of phenylhydrazine free base.

The dehydration reaction for all the aldehydes is susceptible to hydronium ion catalysis between pH 6—8 (Figure 2). The appropriate rate constants are in Table 2.

Discussion

Sayer *et al.*[14] noted that the catalysed formation of the aminomethanol from the reaction of nitrogen nucleophiles with carbonyl compounds proceeds by two separate and concurrent pathways: (i) general acid catalysis of the amine attack on the carbonyl group occurs in a more-or-less concerted manner, and (ii) a stepwise process that involves the uncatalysed formation of a zwitterion intermediate, $T^{\pm}$, that is subsequently trapped by a kinetically significant proton-transfer process involving acids and water. For weakly basic amines and/or aldehydes for which the value of $K_{ad.}$, the equilibrium constant for aminomethanol formation, is small, the predominant pathway of the hydronium ion-catalysed formation is the concerted pathway. For more strongly basic amines, or amines and aldehydes with larger values of $K_{ad.}$, the intermediate $T^{\pm}$ is stabilised and the stepwise pathway is favoured. Contribution of the stepwise pathway to the observed rate of aminomethanol formation is shown as breaks in the pH–rate profiles indicative of changes in the rate-determining step that cannot be accounted for by the transition from aminomethanol formation to dehydration. Our results are in agreement with those reported by Sayer *et al.*[14]

Table 5. Catalytic constants of several acids for the reaction of phenylhydrazine with benzaldehyde, 4-chlorobenzaldehyde, 1-naphthaldehyde, 2-naphthaldehyde, 2-formyl-1,6-methano[10]annulene, and 3-formyl-1,6-methano[10]annulene in 50% aqueous ethanol (v/v) at 25.0 °C, and ionic strength 0.20M

Aldehyde	Catalyst	pK'_a	pH	Concn. (M)	$k_{cat.}$ (M^{-2} s^{-1})
Benzaldehyde	H_3O^{+a}	−1.74	0.25—2.0		2.0×10^3
	$NCCH_2CO_2H$	2.83	2.80	0.025—0.125	4.7×10^2
	$ClCH_2CO_2H$	3.29	3.26	0.025—0.125	3.9×10^2
	HCO_2H	4.03	3.92	0.025—0.125	2.5×10^2
	$BrCH_2CH_2CO_2H$	4.71	4.56	0.025—0.125	1.7×10^2
	AcOH	5.22	5.20	0.025—0.125	1.2×10^2
	PHH^{+b}	4.91	3.90	0.025—0.125	2.8×10^2
4-Chlorobenzaldehyde	H_3O^+	−1.74	0.25—2.0		2.4×10^3
	$NCCH_2CO_2H$	2.83	2.81	0.025—0.125	7.1×10^2
	$ClCH_2CO_2H$	3.29	3.28	0.025—0.125	5.4×10^2
	HCO_2H	4.03	3.92	0.025—0.125	3.9×10^2
	$BrCH_2CH_2CO_2H$	4.71	4.56	0.025—0.125	2.3×10^2
	AcOH	5.22	5.20	0.025—0.125	1.9×10^2
	PHH^+	4.91	3.90	0.025—0.125	2.9×10^2
1-Naphthaldehyde	H_3O^+	−1.74	0.25—2.0		1.1×10^3
	$NCCH_2CO_2H$	2.83	2.85	0.025—0.125	2.0×10^2
	$ClCH_2CO_2H$	3.29	3.21	0.025—0.125	1.8×10^2
	HCO_2H	4.03	3.98	0.025—0.125	0.43×10^2
	$BrCH_2CH_2CO_2H$	4.71	4.72	0.025—0.125	0.11×10^2
	AcOH	5.22	5.19	0.025—0.125	0.10×10^2
	PHH^+	4.91	3.90	0.025—0.125	0.074×10^2
2-Naphthaldehyde	H_3O^+	−1.74	0.25—2.0		1.5×10^3
	$NCCH_2CO_2H$	2.83	2.85	0.025—0.125	3.6×10^2
	$ClCH_2CO_2H$	3.29	3.21	0.025—0.125	2.1×10^2
	HCO_2H	4.03	3.98	0.025—0.125	0.43×10^2
	$BrCH_2CH_2CO_2H$	4.71	4.72	0.025—0.125	0.25×10^2
	AcOH	5.22	5.19	0.025—0.125	0.13×10^2
	PHH^+	4.91	3.90	0.025—0.125	—
2-Formyl-1,6-methano-[10] annulene	H_3O^+	−1.74	0.25—2.0		5.2×10^2
	$NCCH_2CO_2H$	2.83	2.85	0.025—0.125	5.6×10^1
	$ClCH_2CO_2H$	3.29	3.21	0.025—0.125	4.8×10^1
	HCO_2H	4.03	3.98	0.025—0.125	1.8×10^1
	$BrCH_2CH_2CO_2H$	4.71	4.72	0.025—0.125	1.65×10^1
	AcOH	5.22	5.19	0.025—0.125	1.12×10^1
	PHH^+	4.91	3.90	0.025—0.125	2.1×10^1
3-Formyl-1,6-methano-[10]annulene	H_3O^+	−1.72	0.25—2.0		1.1×10^3
	$NCCH_2CO_2H$	2.83	2.85	0.025—0.125	1.1×10^2
	$ClCH_2CO_2H$	3.29	3.21	0.025—0.125	0.98×10^2
	HCO_2H	4.03	3.98	0.025—0.125	0.35×10^2
	$BrCH_2CH_2CO_2H$	4.71	4.72	0.025—0.125	0.21×10^2
	AcOH	5.22	5.19	0.025—0.125	0.95×10^2
	PHH^+	4.91	3.90	0.025—0.125	—

[a] Hydronium ion. [b] Phenylhydrazinium ion.

With phenylhydrazine (pK_a 5.26 in 20% aqueous ethanol,[23] and 4.91 in 50% aqueous ethanol from this work) it is expected that the catalysed formation of the aminomethanol from 4-chlorobenzaldehyde and phenylhdrazine occurs by the stepwise pathway, with two breaks in the pH profile.

To confirm this hypothesis, we extended the pH–rate profile[18] for the reaction of 4-chlorobenzaldehyde and phenylhydrazine in 20% aqueous ethanol, at 25.0 °C and ionic strength 0.50M up to pH 5.0 (Figure 1). It was possible to see two breaks; one at pH 5 corresponding to the change in the rate-determining step from aminomethanol dehydration to uncatalysed aminomethanol formation, and the second at pH 1 corresponding to the change in the rate-determining step from concerted addition of amine and protonation of the carbonyl oxygen atom. Thus, the reaction proceeds by the stepwise pathway.

However when the same reaction was studied in 50% aqueous ethanol at 25.0 °C and ionic strength 0.20M just one break in the pH–rate profile was observed at pH 5 corresponding to the change in the rate-determining step from aminomethanol dehydraton to uncatalysed aminomethanol formation (Figure 2). Thus, the reaction proceeds by the concerted pathway.

A possible explanation as to why the reaction of 4-chlorobenzaldehyde and phenylhydrazine occurs by the stepwise pathway in 20% aqueous ethanol and by the concentrated pathway in 50% aqueous ethanol may lie in the increased ethanol concentration causing destabilization of the zwitterion intermediate, $T^{\pm}$. This is the first observation of a change in the mechanism of formation of aminomethanol caused by a change in the solvent.

From Figure 2 several similarities for the reaction of phenylhydrazine and the benzaldehydes, the naphthaldehydes, and the formyl-1,6-methano[10]annulenes are observed, illustrating the aromaticity of the last ring.

For all the reactions dehydration of the aminomethanol occurs *via* hydronium ion catalysis. The catalytic constants of the hydrated proton for the reaction are of the same order of magnitude (Table 3). Similarly, the formation of the aminomethanol occurs *via* hydronium ion catalysis up to pH 3. The mechanism of the intermediate formation is the same for each aldehyde. The catalytic constants of the aminomethanol formation and all the aldehydes are about the same order of reactivity.

For all the aldehydes formation of the aminomethanol occurs *via* general acid catalysis by the carboxylic acids and by the phenylhydrazinium ion. The α Brønsted exponent determined using the catalytic constants of the carboxylic acid is the same for the formation of the aminomethanol from phenylhydrazine and benzaldehyde (0.26) or 4-chlorobenzaldehyde (0.25). It is the same and greater for 1-naphthaldehyde (0.62) or 2-naphthaldehyde (0.62). It is of intermediate value for 2-formyl-1,6-methano[10]annulene (0.32) and 3-formyl-1,6-methano[10]annulene (0.44). Why the values of α for phenylhydrazine formation from the various aldehydes studied varies is not completely clear. Perhaps the general acid-catalysed formation of the aminomethanol occurs by a different mechanism.[24–26]

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