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Kinetics of the formation of hemicyanine dyes by the condensation of Fischer's base aldehyde with anilines

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Abstract

The kinetics of the condensation of Fischer's base aldehyde with anilines, yielding hemicyanine dyes, was investigated spectrophotometrically. The study was carried out in aqueous solutions with 30%, 45%, or 60% acetic acid. It was found that the condensation is reversible and first order with respect to each reactant. The apparent second-order rate constant of the process decreased slightly for most of the used anilines, when the acetic acid content of the solvent was increased from 30% to 45% and 60%. The electron-withdrawing substituents on the aromatic ring of anilines were found to increase the observed reaction rate, whereas the electron-donor substituents were found to decrease it. However, when the "true" second-order reaction constants are considered, the reverse is valid. The "true" second-order reaction constants were calculated taking into account that part of the total aniline is protonated (and thus, not available for the condensation reaction). The Hammett plots obtained with these "true" second-order rate constants showed satisfactory correlation coefficients and gave a reaction constant of $\rho = -(1.77 \pm 0.10)$ in 30% AcOH, at 30 °C. The obtained kinetic data, and the reaction constants obtained from the Hammett plots, indicate that the rate-determining step of the studied process is the nucleophilic attack of the free amine on the carbonyl group of Fischer's base aldehyde. Activation parameters of the studied condensation reaction were also determined.

Keywords: Hemicyanine dyes; Condensation reaction; Reaction kinetics; Reaction mechanisms; Hammett equation; Substituent effects

1. Introduction

Hemicyanines are extensively used as textile dyes and several of them (such as C.I. Basic Yellow 21, C.I. Basic Yellow 13, and C.I. Basic Yellow 11) are produced at large scale and are commercially available [1,2]. Besides their use as textile dyes, hemicyanine dyes are promising alternatives for photographic sensitizers [3–7], sensitizers in Grätzel type photocells [8–11], and fluorescent probes for monitoring cell membrane potentials and intracellular pH changes [12–15]. Therefore, there is a great interest in the synthesis and characterization of new hemicyanine dyes [1,16–23]. However, up to now only few works addressed the kinetic aspects of their synthesis [24–26], although it is known that kinetic measurements enable the establishment of structure–reactivity relationships, e.g. by means of Hammett equation [27–34]. Taking into account the above-mentioned applications such structure–reactivity relationships for the synthesis of hemicyanine dyes could be of practical interest.

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An industrial method of hemicyanine dye synthesis is based on the condensation of Fischer's base aldehyde (FBA, 1,3,3-trimethyl-2-methylenindolin-ω-aldehyde) with anilines, in acetic acid (AcOH) medium [1,2,16–21,23]. Therefore, in the present work, the kinetics of the condensation of FBA with differently substituted anilines, in concentrated acetic acid medium, has been investigated. The effect of a large number of substituents on the benzene ring of the anilines upon the reaction rate has been studied in order to identify the rate-limiting step of the process and to establish a structure–reactivity relationship. Moreover, the influence of different reaction conditions, such as acetic acid content of the reaction medium and temperature, on the reaction rate has been also examined.

2. Materials and methods

2.1. Materials

4-Aminoacetanilide, 4-aminobenzonitrile, 4-trifluoromethylaniline, 3- trifluoromethylaniline, 3-aminobenzyl alcohol, 3-aminophenol, 3-anisidine, 3-bromoaniline, 3-chloroaniline, 3-ethylaniline, 4-ethylaniline, 4-fluoroaniline, 4-iodoaniline, and 4-*tert*-butylaniline were purchased from Merck-Schuchardt, Hohenbrunn, Germany. 3-Aminoacetophenone, 3-aminobenzonitrile, 3-fluoroaniline, methyl 3-aminobenzoate, 3-nitroaniline, 3-toluidine, and 4-toluidine were purchased from Fluka Chemie GmbH, Buchs, Switzerland. 4-Aminobenzoic acid was purchased from Kebo AB, Stockholm, Sweden. Glacial acetic acid was purchased from Chimopar, Bucharest, Romania. All chemicals were used as received. 4-Aminobenzenesulfonamide and FBA were synthesized as previously described [35–38]. All solutions were prepared by using demineralized and double-distilled water.

2.2. Kinetic measurements

The observed rate constants of the studied reactions were determined spectrophotometrically by measuring the absorbance of the formed hemicyanine dye in AcOH–water mixture or methanol–water–AcOH mixture. The AcOH content in the AcOH–water mixture was 30%, 45% or 60% (v). The concentration of AcOH in 50% (v) aqueous solution of methanol was varied in the range of 0.052–0.364 mol L^{-1}. Stock solutions of the aldehyde and the anilines were freshly prepared just before each set of measurements. Appropriate volumes from these stock solutions were mixed directly in the quartz cuvette (1 cm optical path length) to obtain the required concentrations of the reactants. The amine was used in concentrations at least 10 times higher than the aldehyde in order to assure pseudo-first-order conditions. As the reaction proceeded, the formation of the hemicyanine dye was followed either at 410 nm (since the resulting dyes exhibit an absorption maximum around this wavelength) or by periodically recording the absorption spectra between 200 nm and 550 nm on a Jasco spectrophotometer (Model V-530, Japan) provided with a thermostated cell holder. The latter procedure was often preferred due to the additional information contained by the spectra (i.e. due to simultaneous observation of the product formation and reactant consumption, and an easier observation at the end of reaction). However, the first approach gives a better time resolution to the measurement. The reference consisted of a cuvette containing acetic acid solution of the same composition as the reaction media. The absorbance values corresponding to a conversion of up to 5% were used for the calculation of rate constants, in order to minimize the effect of the reverse reaction. All experiments were performed at least twice and a difference of maximum 3% of the rate constant was accepted between runs.

3. Results and discussion

Fig. 1 shows successively recorded absorption spectra after mixing 4-aminobenzonitrile and FBA. The spectra display two characteristic absorption peaks, which can be used for kinetic purposes, and a well-defined isosbestic point. The absorption band at 344 nm corresponds to the FBA, whilst the one at 415 nm corresponds to the formed hemicyanine dye. The occurrence of the isosbestic point at 370 nm suggests

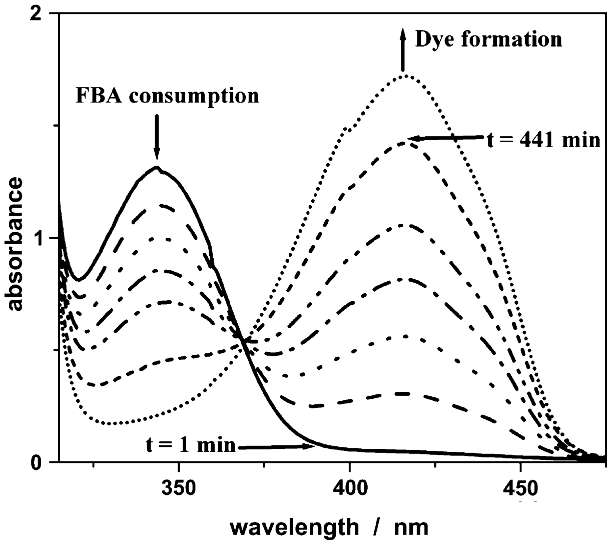


Fig. 1. Successively recorded absorption spectra for a reaction mixture of 4-aminobenzonitrile (4.01 × 10^{-3} mol L^{-1}) and FBA (5.01 × 10^{-5} mol L^{-1}), in 30% aqueous solution of acetic acid, at 30 °C.

Table 1
Initial rates for the reaction of 4-aminobenzonitrile with increasing concentrations of FBA, in 30% aqueous solution of acetic acid, at 30 °C

$[\text{Amine}]_t$ (mol L^{-1})	[FBA] (mol L^{-1})	Initial rate (s^{-1})
6.25×10^{-3}	0.50×10^{-4}	1.53×10^{-4}
6.25×10^{-3}	1.00×10^{-4}	2.92×10^{-4}
6.25×10^{-3}	2.00×10^{-4}	5.28×10^{-4}
6.25×10^{-3}	4.02×10^{-4}	10.17×10^{-4}

that there are no long-lived intermediates involved in the condensation reaction.

3.1. Determination of the reaction order

The first-order kinetics with respect to FBA was determined by the initial rate method. First, the absorbance at 410 nm for mixtures with a constant concentration of 4-aminobenzonitrile and increasing concentrations of FBA (as limiting component) was recorded. Then, the initial rates dA/dt (s^{-1}), were obtained as the slopes of the absorbance (at the beginning of the reaction) vs time plots. They were found to increase linearly with the concentration of FBA as presented in Table 1. $[\text{Amine}]_t$ stands for the total concentration of aniline introduced in the reaction mixture.

The first-order kinetics with respect to the amine was confirmed for four anilines, bearing different substituents on the benzene ring, by using the observed rate constants, k_{obsd}. The observed rate constants were calculated as the slope of the semilogarithmic plot of Eq. (1).

$$\ln(A_\infty - A) = \ln(A_\infty - A_0) - k_{\text{obsd}} t \tag{1}$$

A_∞, A, and A_0 stands for the absorbance at the end of reaction, absorbance at time t, and the initial value of absorbance, respectively. Straight lines with very good correlation coefficients (0.9990–0.9999) were obtained for the first part of the reaction. When k_{obsd} was calculated using the absorbance at 344 nm (i.e. at the maximum absorbance of FBA), the obtained values were systematically slightly lesser than those obtained following the dye formation (at the maximum absorbance of the dye). As the successively recorded spectra show in Fig. 1, this difference could be due to the overlap between the tail of the absorbance peak corresponding to the dye and the absorbance peak corresponding to the aldehyde. Therefore, all reported rate constants were obtained following the dye formation. Observed rate constants, determined at different excess concentrations of amine and a constant concentration of FBA, were linearly dependent on the total concentration of the aniline $[\text{Amine}]_t$ (see Fig. 2). From the plot of k_{obsd} vs $[\text{Amine}]_t$ two important conclusions can be deduced. First, the straight lines do not pass through the origin, indicating a reversible process. The reversibility of the condensation is further proved by the fact that larger excess concentrations of the amine gave higher values of A_∞, corresponding to higher concentrations of the formed hemicyanine dyes, with the same concentration of FBA as limiting component. Second, the linear dependence of k_{obsd} vs $[\text{Amine}]_t$ indicates that the forward process (i.e. the hemicyanine dye formation) is a first-order reaction with respect to the amine.

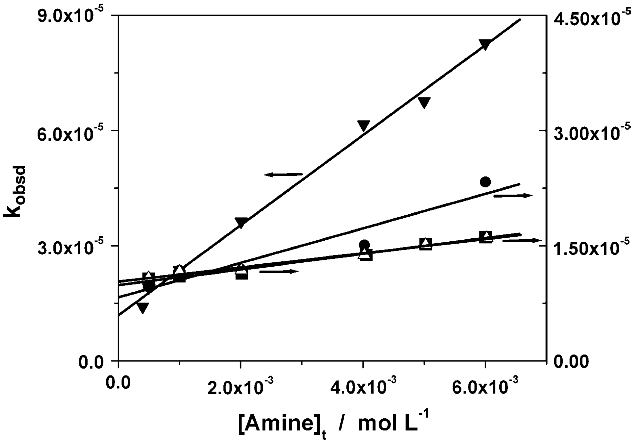


Fig. 2. Observed rate constants as a function of total amine concentrations in the condensation with FBA. Experimental conditions: 3-toluidine (■), aniline (●), 4-*tert*-butylaniline (△), 4-aminobenzonitrile (▼), [FBA] = 5.00×10^{-5} mol L^{-1}, 30% acetic acid solution, at 30 °C.

Therefore, it is obvious that at constant acidity, the forward reaction obeys a second-order rate law, first order with respect to both the amine and the FBA, as described by Eq. (2).

$$\text{rate} = k_{1\text{app}}[\text{FBA}][\text{Amine}]_t \tag{2}$$

Moreover, the condensation between the anilines and FBA, as a reversible process is represented by Eq. (3) and characterized by $k_{1\text{app}}$, k_{-1}, and K. Here $k_{1\text{app}}$ is the apparent second-order rate constant of the forward reaction, k_{-1} is the rate constant of the reverse reaction, and K is the equilibrium constant defined as $K = k_{1\text{app}}/k_{-1}$

$$\text{FBA} + \text{X–C}_6\text{H}_4\text{–NH}_2 \xrightleftharpoons{\text{AcOH}} \text{Hemicyanine dye as acetate} + \text{H}_2\text{O} \quad k_{1\text{app}}, k_{-1}, K \tag{3}$$

Under the used experimental conditions (i.e. excess concentration of the anilines in concentrated AcOH solutions), the observed rate constant will be described by Eq. (4).

$$k_{\text{obsd}} = k_{1\text{app}}[\text{Amine}]_t + k_{-1} \tag{4}$$

Anilines with substituents displaying different electronic effects were selected for the above study. It was found that electron-withdrawing substituents increase the rate of the condensation reaction. The apparent second-order rate constant of the forward process, $k_{1\mathrm{app}}$, as the slope obtained from Fig. 2, was $11.74 \times 10^{-3}\ \mathrm{L\,mol^{-1}\,s^{-1}}$ for 4-aminobenzonitrile, $2.25 \times 10^{-3}\ \mathrm{L\,mol^{-1}\,s^{-1}}$ for aniline, $1.02 \times 10^{-3}\ \mathrm{L\,mol^{-1}\,s^{-1}}$ for 3-toluidine, and $0.92 \times 10^{-3}\ \mathrm{L\,mol^{-1}\,s^{-1}}$ for the 4-*tert*-butylaniline. However, the rate constants of the reverse reaction (as the intercepts from Fig. 2) were quite close to each other and small. This indicates that the reverse reaction is not significantly influenced by the substituent on the benzene ring of the anilines. This could be due to a long distance between the substituent and the reaction center. The equilibrium constant ($K = k_{1\mathrm{app}}/k_{-1}$) calculated from the kinetic data displayed in Fig. 2, was $991.8\ \mathrm{L\,mol^{-1}}$ for 4-aminobenzonitrile, $272.8\ \mathrm{L\,mol^{-1}}$ for aniline, $104.2\ \mathrm{L\,mol^{-1}}$ for 3-toluidine, and $88.6\ \mathrm{L\,mol^{-1}}$ for 4-*tert*-butylaniline. Correspondingly, higher values of A_∞, indicating higher concentrations of the formed hemicyanine dyes, were experimentally observed for the reactions with anilines bearing electron-withdrawing substituents than for the reactions with the anilines bearing electron-donating substituents.

3.2. The effect of the acetic acid concentration on the reaction rate

The effect of acetic acid content of the reaction media on the condensation rate has been also investigated by using aqueous solutions with 30%, 45%, or 60% (v) acetic acid. It was observed that, increasing the acetic acid content of the reaction medium decreases slightly the rate of the condensation reaction for most of the studied amines. Fig. 3 presents the variation of k_{obsd} with the concentration of 4-aminobenzonitrile at different concentrations of acetic acid in the reaction medium.

The slope of the plots, i.e. the apparent second-order rate constant of the forward reaction, diminishes from $11.74 \times 10^{-3}\ \mathrm{L\,mol^{-1}\,s^{-1}}$ to $7.39 \times 10^{-3}\ \mathrm{L\,mol^{-1}\,s^{-1}}$ and $4.59 \times 10^{-3}\ \mathrm{s^{-1}\,L\,mol^{-1}\,s^{-1}}$ as the content of the acetic acid increases from 30% to 45% and 60%, respectively. The decrease of the free amine concentration and increase of the protonated amine concentration, when the acetic acid concentration is increased, can explain such a behavior. Since the active form of the anilines in the nucleophilic attack is the free amine, and the concentration of this free amine is decreasing with increasing concentrations of acetic acid, the reaction rate decreases with increasing concentrations of acetic acid.

In order to identify a possible acid catalysis [27,32,33,39,40], several measurements were carried out in 50% (v) aqueous solution of methanol containing much lower concentrations of acetic acid than in the above experiments. At lower acid concentrations the decrease in the concentration of the free amine is less pronounced, therefore, one can expect that the effect of an acid catalysis can be easily detected. The initial rate method showed that reaction rates increased linearly when the acetic acid concentration increased from $0.052\ \mathrm{mol\,L^{-1}}$ to $0.364\ \mathrm{mol\,L^{-1}}$. The plot of the initial rate as a function of the acetic acid concentration (see Fig. 4) is a straight line, which does not pass through the origin. Such behavior could be due to an acid catalyzed process occurring in parallel with a non-catalyzed process [27,32,33].

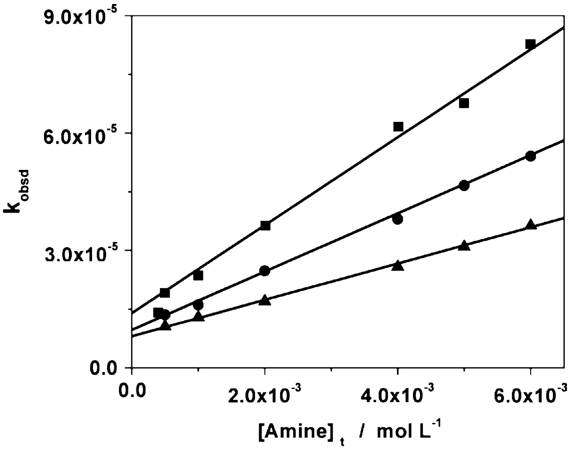


Fig. 3. Observed rate constants at different 4-aminobenzonitrile concentrations in the condensation with FBA in 30% acetic acid (■), 45% acetic acid (●), or 60% acetic acid (▲) solution. Experimental conditions: [FBA] = $5.00 \times 10^{-5}\ \mathrm{mol\,L^{-1}}$, at 30 °C.

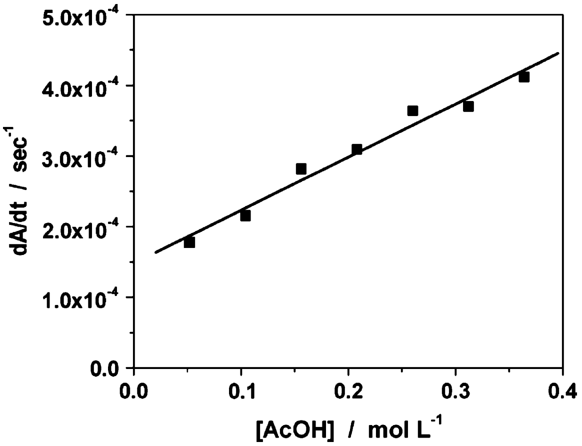


Fig. 4. Initial rates of the condensation of 4-aminobenzonitrile with FBA in 50% aqueous solution of methanol containing different concentrations of acetic acid. Experimental conditions: $[\mathrm{Amine}]_t = 6.00 \times 10^{-3}\ \mathrm{mol\,L^{-1}}$, $[\mathrm{FBA}] = 3.00 \times 10^{-4}\ \mathrm{mol\,L^{-1}}$, $\lambda = 410$ nm, at 30 °C.

Table 2
Second-order rate constants for the condensation of *meta* and *para* substituted anilines with FBA

Anilines, σ [44,45], λ_{max}[a] of the resulting dye (nm)	k'_{1app} ($L\,s^{-1}\,mol^{-1}$)			k'_1 ($L\,s^{-1}\,mol^{-1}$)		
	30% AcOH	45% AcOH	60% AcOH	30% AcOH	45% AcOH	60% AcOH
4-Aminobenzonitrile, 0.66, 415	2.36×10^{-2}	–	–	0.24	–	–
4-Aminobenzenesulfonamide, 0.57, 414	3.39×10^{-2}	–		0.24	–	–
4-Aminobenzotrifluoride, 0.54, 409	4.58×10^{-2}	–	–	0.61	–	–
4-Aminobenzoic acid, 0.45	2.69×10^{-2}	–	–	0.80	–	–
4-Iodoaniline, 0.18, 415	2.33×10^{-2}	–	–	1.5	–	–
4-Fluoroaniline, 0.06	8.74×10^{-3}	–	–	3.85	–	–
4-Aminoacetanilide, 0.00, 418	6.19×10^{-3}	–	–	7.81	–	–
4-Ethylaniline, −0.15, 413	7.74×10^{-3}	–	–	9.51	–	–
4-Toluidine, −0.17, 413	5.99×10^{-3}	–	–	10.26	–	–
4-*tert*-Butylaniline, −0.2, 414	2.65×10^{-3}	–	–	12.6	–	–
4-Aminophenol, −0.37	2.44×10^{-3}	–	–	15.83	–	–
3-Nitroaniline, 0.71, 406	4.98×10^{-2}	4.12×10^{-2}	3.89×10^{-2}	0.47	0.42	0.59
3-Aminobenzonitrile, 0.56, 408	3.04×10^{-2}	2.74×10^{-2}	3.71×10^{-2}	0.55	0.62	0.5
3-Aminobenzotrifluoride, 0.43, 407	–	3.90×10^{-2}	2.94×10^{-2}	–	1.33	1.31
3-Bromoaniline, 0.39, 410	2.51×10^{-2}	1.91×10^{-2}	–	1.46	1.43	–
3-Aminoacetophenone, 0.38, 410	2.90×10^{-2}	2.84×10^{-2}	1.89×10^{-2}	1.66	2.30	2.03
3-Chloroaniline, 0.37, 410	4.22×10^{-2}	3.52×10^{-2}	1.48×10^{-2}	1.48	1.74	1.67
Methyl 3-aminobenzoate, 0.37, 409	2.74×10^{-2}	1.20×10^{-2}	1.04×10^{-2}	1.23	1.44	1.03
3-Fluoroaniline, 0.34, 409	–	3.85×10^{-2}	2.64×10^{-2}	–	2.73	2.45
3-Anisidine, 0.12, 409	1.50×10^{-2}	1.28×10^{-2}	1.25×10^{-2}	3.64	4.15	6.81
3-Aminophenol, 0.12, 411	1.24×10^{-2}	–	6.82×10^{-3}	3.86	–	4.06
3-Aminobenzyl alcohol, 0.00, 410	1.09×10^{-2}	9.90×10^{-3}	6.34×10^{-3}	5.91	6.85	6.60
Aniline, 0.00, 410	3.88×10^{-3}	5.54×10^{-3}	4.91×10^{-3}	3.96	8.75	13.94
3-Ethylaniline, −0.07, 410	7.89×10^{-3}	–	–	10.16	–	–
3-Toluidine, −0.07, 410	2.68×10^{-3}	5.67×10^{-3}	5.01×10^{-3}	7.76	8.03	12.02

[a] λ_{max} – Absorption maximum of the resulting dyes in 30% AcOH.

3.3. The effect of the aniline substituent on the reaction rate

In order to investigate the structure–reactivity correlation into more details, a Hammett plot was made based on 24 *para* or *meta* substituted anilines. Absorbance data corresponding to a small degree of conversion (at most 5%) were used in order to minimize the contribution of the reverse reaction. Within this incipient part of the reaction, the overall process can be considered as consisting of only the forward process, and the observed rate constant becomes $k_{obsd} = k'_{1app}[\text{Amine}]_t$. Therefore, the apparent second-order rate constant can be obtained with good approximation by dividing k_{obsd} with the total concentration of the amine. The second-order rate constants from this study will be noted as k'_{1app} to distinguish them from those where the rate constant of the reverse reaction was also considered (denoted k_{1app}). Using k'_{1app}, the "true" second-order rate constant (k'_1) was also calculated, taking into account that part of the amine in the reaction medium is protonated and, thus, not available for the condensation reaction. k'_{1app} and k'_1 values corresponding to each amine are presented in Table 2.

Fig. 5 shows that the structure–reactivity relationship of the reaction of FBA with *para* and *meta* substituted amines, in 30% aqueous solution of AcOH, can be rather poorly described by the Hammett equation. There is a large dispersion of the obtained data (*R*, the correlation coefficient being only 0.91). Moreover, the slope of the Hammett representation (i.e. the reaction constant, ρ) is positive and small (1.24). All these findings are in contrast with the nucleophilic attack of the aniline on the aldehyde as rate-limiting step of the condensation in acidic media. Nucleophilic attack as rate-limiting step is usually indicated by a reverse

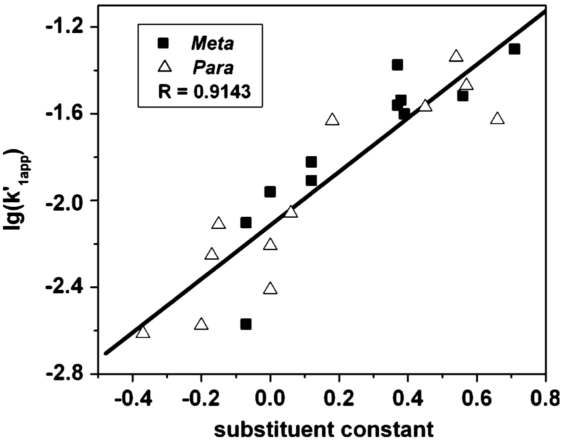


Fig. 5. Hammett representation (using log k'_{1app} as a function of σ) of the influence of amine substituents in *meta* and *para* positions on the condensation reaction rate, in 30% acetic acid solution, at 30 °C.

substituent effect, and a reaction constant with a negative sign and an absolute value of 2 [40]. However, it is noteworthy that the condensation of amines with aldehydes is a complex reaction, which is often characterized both by non-linear Hammett correlations [27,32,33] and by different rate-limiting steps depending on the working conditions [39,41]. The lower value of the obtained ρ could indicate that the reaction center is far from the substituent on the benzene ring of anilines [42], whilst its positive sign is compatible with an acid ionization as rate-limiting step [31,34].

The large scattering of points, as well as the decreasing reaction rate with increasing concentrations of AcOH in the reaction mixture, might be due to the protonation of the amine [23,29], taking into account that the condensation requires amine as free base [23,27,32,33,43]. Therefore, to calculate the "true" second-order rate constants (k'_1) for all the investigated reactions, the following equilibrium has been taken into consideration:

$$CH_3COOH + X{-}C_6H_4{-}NH_2 \rightleftarrows CH_3COO^- + X{-}C_6H_4{-}NH_3^+ \quad K' \tag{5}$$

The equilibrium constant characterizing this process is given by Eq. (6)

$$K' = \frac{[CH_3COO^-]\,[XC_6H_4NH_3^+]}{[CH_3COOH]\,[XC_6H_4NH_2]} = \frac{K_{AcOH}}{K_{BH^+}} \tag{6}$$

where K_{AcOH} and K_{BH^+} are the equilibrium constants characterizing the dissociation of the acetic acid and of the protonated amine, respectively. By using K_{AcOH}, K_{BH^+}, and a method described in the literature [29], the free amine concentration has been calculated for all the substituted anilines. Subsequently, the "true" second-order rate constants were also calculated as $k'_1 = k_{obsd}/[XC_6H_4NH_2]_{free}$. It is worth mentioning that both K_{AcOH} and K_{BH^+} are affected in a similar manner by changes in temperature or solvent composition. Therefore, their ratio was considered to remain constant. A new Hammett plot was then built with the obtained "true" second-order rate constants. As shown in Fig. 6, the structure–reactivity relationship is much better described by the Hammett equation when using these "true" second-order rate constants.

The scattering of points is not so pronounced (R, the correlation coefficient, is 0.97) and the reaction constant is negative.

$$\log k'_1 = -(1.77 \pm 0.10)\sigma + (0.73 \pm 0.03) \tag{7}$$

Moreover, the ρ value is close to that obtained for condensation of anilines with benzaldehyde [40]. Using the *meta* substituted anilines, Hammett plots with satisfactory correlation coefficients were obtained for the reactions carried out in 45% and 60% aqueous solution of AcOH as well (see Eqs. (8) and (9)).

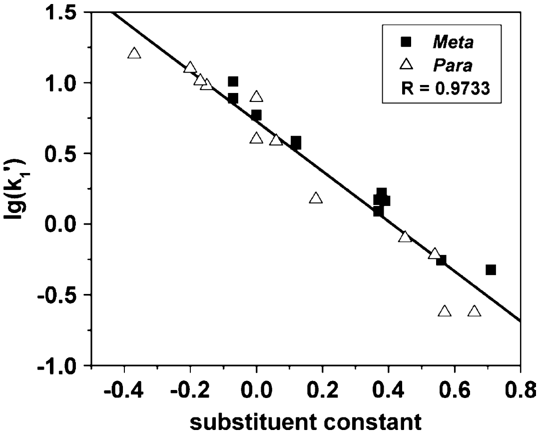


Fig. 6. Hammett representation (using $\log k'_1$ as a function of σ) of the influence of amine substituents in *meta* and *para* positions on the condensation reaction rate, in 30% aqueous solution of AcOH, at 30 °C.

$$\log k'_1 = -(1.73 \pm 0.11)\sigma + (0.87 \pm 0.04) \quad R = 0.980 \text{ (in 45\% AcOH)} \tag{8}$$

$$\log k'_1 = -(1.91 \pm 0.18)\sigma + (0.95 \pm 0.07) \quad R = 0.960 \text{ (in 60\% AcOH)} \tag{9}$$

Therefore, the experimentally obtained reaction rates, which are greater for amines with electron-withdrawing substituents than for amines with electron–donor substituents, may be explained by the larger extent of protonation in the last case. The electron-donating substituents increase both the nucleophilic character of anilines and their basicity. The greater nucleophilic character of the anilines substituted with electron-donating groups is translated into a greater condensation rate. However, the greater basicity of the anilines substituted with electron-donating groups causes also a shift of the equilibrium given by Eq. (5) towards right and, thus, a diminution of the free base concentration in acidic media. As a consequence, the electron-donating substituents from the benzene ring of anilines have two opposite effects upon the reaction rate with aldehydes in acidic media. When the extent of the protonation exceeds in importance the accelerating effect of the electron–donor substituents in the nucleophilic attack, the condensation reaction rate is diminished [43].

3.4. The effect of temperature on the reaction rate

The effect of the temperature on the apparent second-order rate constant (k'_{1app}) was investigated in the range of 19–52 °C for a selection of five anilines

Table 3
Activation parameters for different anilines in reaction with FBA

Amine	E_a (kJ mol^{-1})	$\Delta H^{\neq}$ (kJ mol^{-1})	$\Delta S^{\neq}$ (J mol^{-1} K^{-1})	$\Delta G^{\neq}$ (kJ mol^{-1})[a]
4-Aminobenzonitrile	39.7	37.2	−159.1	84.6
3-Aminobenzotrifluoride	56.7	54.1	−106.7	85.9
Aniline	62.8	60.2	−93.4	88.0
4-*tert*-Butylaniline	61.5	59.0	−100.0	88.8
3-Toluidine	66.9	64.4	−81.5	88.7

[a] Calculated as $\Delta G^{\neq} = \Delta H^{\neq} - T\,\Delta S^{\neq}$ at $T = 298$ °K.

with both electron-donating and electron-withdrawing substituents. From the obtained data activation parameters were calculated. The linear Arrhenius plots and Eyring plots had good correlation coefficients ($R = 0.9797$–0.9992, and $R = 0.9786$–0.9992, respectively). The obtained data are summarized in Table 3.

Smaller activation energies and enthalpies were found for anilines with substituents characterized by electron-withdrawing properties. The activation entropies were negative in all the investigated cases (with the largest negative activation entropy for the aniline with the strongest electron-withdrawing substituent). A slightly larger $\Delta G^{\neq}$ was obtained for anilines with electron–donor substituents than for anilines with electron-withdrawing substituents.

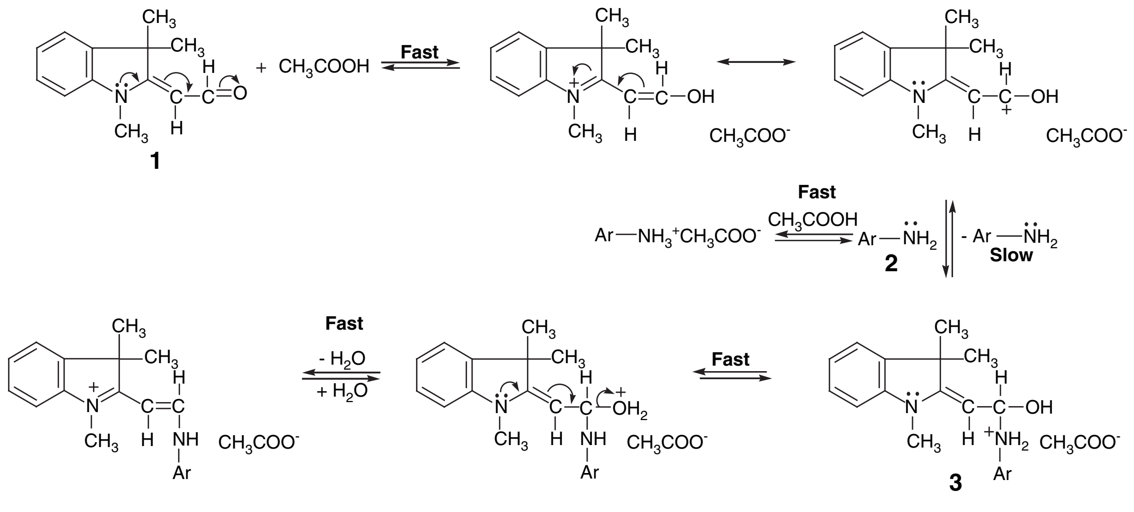
The linear plot of $\Delta H^{\neq}$ vs $\Delta S^{\neq}$ ($R = 0.996$) indicates that there is no change in mechanism for these anilines [25]. It is also noteworthy that the obtained activation parameters are comparable with those found for the formation of Schiff bases [27,32].

3.5. Reaction mechanism

Our study, concerning the structure–reactivity relationship in the condensation of FBA **1** with different anilines **2** in concentrated AcOH, clearly shows that anilines substituted with electron–donor groups increase the rate of the condensation, while anilines substituted with electron-withdrawing groups decrease the rate of condensation when compared to the unsubstituted aniline. These data indicate the nucleophilic attack of the free amine on the carbonyl of FBA and/or its conjugated acid as the only possible rate-determining step of the formation of hemicyanine dyes **3**. The suggested mechanism is presented in Scheme 1.

4. Conclusions

The kinetic study on the reaction of different anilines with FBA, in concentrated AcOH, has shown that the condensation process, resulting in different hemicyanine dyes, is of first order with respect to each reactant. When using anilines bearing electron-withdrawing substituents the observed reaction rates were larger than the ones obtained with anilines substituted with electron–donor groups. However, when the concentration of the free amine was taken into account the anilines substituted with electron–donor groups were found to increase the rate of the condensation, i.e. a reverse substituent effect was obtained. Such a behavior sustains the nucleophilic attack of the free amine on the carbonyl group of FBA



Scheme 1. Mechanism of the formation of hemicyanine dyes by the condensation of Fischer's base aldehyde with anilines.

as the rate-determining step of the addition–elimination process. Obviously, the electron–donor substituents increase both the nucleophilic character of anilines and their basicity, but at high concentrations of acetic acid the decrease of the free amine concentration overshadows the benefic effect of the electron–donor substituents on the reaction rate.

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References

[1] Baer DR. In: Venkataraman K, editor. The chemistry of synthetic dyes, vol. IV. Academic Press; 1971. p. 185–6.

[2] Raue R. In: Elvers B, Hawkins S, Schulz G, editors. Ullmann's encyclopedia of industrial chemistry, vol. A16. KgaA: Wiley-VCH Verlag GmbH & Co; 1990. p. 487–534.

[3] Shiba K, Sueyoshi T, Sato A, Kubodera S, Tsubota M. Photographic emulsion containing optically dye-sensitized silver halide grains of less than 0.2 micron. US Pat 3,706,566; 1972.

[4] Sato A, Shiba K, Hinata M. Spectrally sensitized photographic silver halide emulsion. US Pat 3,770,440; 1973.

[5] Nakazawa Y, Nakamura Y, Sueyoshi T, Sato A. Fine grain silver halide photographic emulsion containing hemicyanine sensitizing dye. US Pat 3,788,859; 1974.

[6] Lincoln LL, Heseltine DW. Sensitized silver halide emulsions containing N, α-alkylene bridged sensitizing dyes. US Pat 3,384,489; 1968.

[7] Kameoka K, Miyata J, Okazaki M, Sasaoka S. Silver halide photographic light-sensitive material and high contrast negative image forming process using them. US Pat 4,725,532; 1988.

[8] Wang Z-S, Li F-Y, Huang C-H. Photocurrent enhancement of hemicyanine dyes containing RSO_3 – group through treating TiO_2 films with hydrochloric acid. J Phys Chem B 2001;105(38):9210–7.

[9] Stathatos E, Lianos P, Laschewsky A, Ouari O, Cleuvenbergen P. Synthesis of a hemicyanine dye bearing two carboxilic groups and its use as a photosensitiser in dye-sensitized photoelectrochemical cells. Chem Mater 2001;13(11):3888–92.

[10] Stathatos E, Lianos P, Laschewsky A. Photophysical properties of an amphiphilic cationic hemicyanine dye in solution and adsorbed on a TiO_2 mesoporous film. Langmuir 1997;13(2): 259–63.

[11] Yao Q-H, Meng F-S, Li F-Y, Tian H, Huang C-H. Photoelectric conversion properties of four novel carboxylated hemicyanine dyes on TiO_2 electrode. J Mater Chem 2003;13(5):1048–53.

[12] Grinvald A, Hildesheim R, Farber IC, Anglister L. Improved fluorescent probes for the measurement of rapid changes in membrane potential. Biophys J 1982;39(3):301–8.

[13] Fromherz P, Roecker C. Staining of biomembranes with amphiphilic hemicyanine dyes. Berichte der Bunsen-Gesellschaft. [Ber Bunsenges Phys Chem] 1994;98(1):128–31.

[14] Fromherz P, Mueller CO. Voltage-sensitive fluorescence of amphiphilic hemicyanine dyes in neuron membrane. Biochim Biophys Acta 1993;1150(2):111–22.

[15] Fluhler E, Burnham VG, Loew LM. Spectra, membrane binding, and potentiometric responses of new charge shift probes. Biochemistry 1985;24(21):5749–55.

[16] Kast H. Basic dyes. US Pat 4,176,229; 1979.

[17] Kuehlthau HP. Methine dyestuffs. US Pat 3,786,047; 1974.

[18] Langfeld HW, Barbacaru E. Spectrele de absorbtie ale unor coloranti metinici indolinici. Rev Chim (Buc.) 1981;32(3):230–2.

[19] Loew P, Zink R, Koller S. Cationic dyes. US Pat 4,251,656; 1981.

[20] Mohr R, Hahnke M. Quaternary and basic azamethine compounds and their use as colorants. US Pat 4,344,879; 1982.

[21] Obayashi K, Oka R, Takada H, Taura S. Basic dyes. Jpn Pat 39,027,121 [Chem Abstr 62:67017]; 1964.

[22] Jedrzejewska B, Kabate J, Pietrzak M, Paczkowski J. Hemicyanine dyes: synthesis, structure and photophysical properties. Dyes Pigments 2003;58(1):47–58.

[23] Spiliadis A, Vladutiu L, Zaharia M. A study concerning Fischer aldehyde condensation with aromatic amines. Rev Chim (Buc.) 1975;26(11):868–901.

[24] Kramer ND, Bisauta LP, Bato R. Kinetics of the condensation of *N*-methyl-4-picolinium iodide with *p*-dimethylaminobenzaldehyde in aqueous ethanol. J Org Chem 1974;39(21):3132–6.

[25] Issa IM, Defallah EM, Mahmoud MR, Khalil ZH, Abdel-Hamid R. Kinetics of the base-catalyzed reaction of vanilline, *p*-hydroxybenzaldehyde, *p*-*N*-dimethylbenzaldehyde and salicylaldehyde with α-picoline ethiodide. Indian J Chem B 1976;14(4):296–8.

[26] Oszczapowicz J, Orlinski R, Jaroszeweka J, Kaminska E. Cyanine dyes. Part III. Amidines. Part X. Rates of reaction on *N*, *N′*-diphenylformamidines with *N*-alkylepidinium iodides. Pol J Chem 1982;56(4–5–6):725–33.

[27] Santerre GM, Hansrote CJJ, Crowell TI. The reaction of aromatic aldehydes with *n*-butylamine. Acid catalysis and substituent effects. J Am Chem Soc 1958;80(5):1254–7.

[28] Pierpoint AC, Hapeman CJ, Torrents A. Linear free energy study of ring-substituted aniline ozonation for developing treatment of aniline based pesticide wastes. J Agric Food Chem 2001;49(8): 3827–32.

[29] Karunakaran C, Kamalam R. Structure–reactivity correlation of anilines in acetic acid. J Org Chem 2002;67(4):1118–24.

[30] Hodges GR, Lindsay Smith JR, Oakes J. Mechanism of oxidation of azo dyes by a sterically hindered anionic oxoiron(IV) porphyrin in aqueous solution. J Chem Soc Perkin Trans 1998;2(3):617–27.

[31] Hammett LP. The effect of structure upon the reactions of organic compounds. Benzene derivatives. J Am Chem Soc 1937;59(1): 96–103.

[32] Crowell TI, Bell CE, O Brien DH. Extrathermodynamic relationships in Schiff base formation. J Amer Chem Soc 1964;86(22): 4973–6.

[33] Cordes EH, Jencks WP. General acid catalysis of semicarbazone formation. J Amer Chem Soc 1962;84(22):4319–28.

[34] Brändström A. Estimation of electronic effects in aromatic systems. J Chem Soc Perkin Trans 1999;2(9):1847–53.

[35] Ionescu M, Panea I. Sulfonamides with thiourea fragment. Studia Univ Babeş-Bolyai Chemia 1966;11(1):109–14.

[36] Fritz H. α, β,-Unsaturated β-anilinocarbonyl compounds as model substances for the chromophore of C-cumarine-III (C-fluorocumarine). Chem Ber 1959;92:1809–17.

[37] Gelmo P. Sulphamides of *p*-aminobenzenesulphonic acid. J Prakt Chem 1908;77:369–82.

[38] Panea I, Cristea I. ^{1}H-NMR study of condensation products of 1-(2-pyrimidinyl)-3-methylpyrazolin-5-ones with heterocyclic aldehydes. Studia Univ Babeş-Bolyai Chemia 1996;41(1):9–12.

[39] Carey FA, Sundberg RJ. Advanced organic chemistry. Part A: structure and mechanism. New York: Plenum Press; 1990. p. 451–2.

[40] Pratt EF, Kamlet MJ. Reaction rates by distillation. IX. The condensation of anilines with benzaldehydes. J Org Chem 1961; 26(10):4029–31.

[41] Page MI. Reactions of aldehydes and ketones and their derivatives. In: Knipe AC, Watts WE, editors. Org React Mech John Wiley and Sons; 1987. p. 1–27 [published 1989].

[42] Willi AV. Effect of substitution on the acidity constants of benzenesulfonamides. Helv Chim Acta 1956; 39:46–53.

[43] Christen HR, Vogtle F. Organische Chemie, Von den Grundlagen zur Forschung. Frankfurt am Main: Otto Sale Verlag; 1988. p. 653.

[44] Hansch C, Leo A, Unger SH, Kim KH, Nikaitani D, Lien EJ. "Aromatic" substituent constants for structure–activity correlations. J Med Chem 1973;16(11):1207–16.

[45] Hansch C, Leo A, Taft RW. A survey of Hammett substituent constants and resonance and field parameters. Chem Rev 1991;91(2):165–95.