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The Hydrolysis of Pyrrolidine Green and Some Derivatives. Part 2.[1] The Kinetics of the Hydrolysis of Some 3-Substituted Derivatives of Pyrrolidine Green

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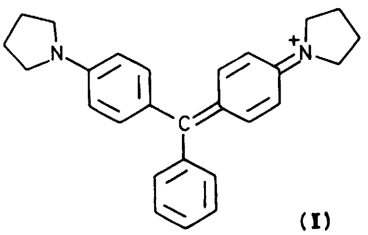
Rate constants have been measured for the reactions of hydroxide ion with Pyrrolidine Green and its 3-Me, 3-Br, 3-CF_3, and 3-NO_2 derivatives in aqueous solution. The substituents affect the rate of hydrolysis to an extent linearly related to the appropriate Hammett substituent constant. Thermodynamic parameters $\Delta H^\ddagger$ and $\Delta S^\ddagger$ have been determined for each dye. The existence of an isokinetic relationship has been established by analysis of Arrhenius plots and confirmed by other methods.

Numerous chemical,[2,3] biological,[4,5] and industrial[6] applications of triphenylmethane dyes are known. The dyes show only poor to moderate fastness to washing and thus information on the hydrolysis of the dyes is important. In order to augment our knowledge of the protolytic and hydration equilibria and of the rates of hydrolysis of triphenylmethane dyes, we have extended our study of Pyrrolidine Green (I) to ascertain the influence of *meta*-substitution in the phenyl ring. The reactions of the dyes with water molecules and hydroxide ions over the pH range 10—11.5, within a temperature range 293.2—313.2 K at ionic strengths 0.005—0.5 mol dm^{-3}, are now reported.



(I)

Experimental

The kinetic studies were carried out using the procedures described previously.[7] Spectrophotometric measurements were made at the wavelength of maximum absorption pertinent to each dye using a Pye–Unicam SP6-350 spectrophotometer. The leuco-bases and dye perchlorates of the 3-bromo- and 3-nitro-derivatives were prepared by methods analogous to those described for Pyrrolidine Green itself. The remaining perchlorates were obtained from the dye-bases, themselves prepared by the reaction between 4,4′-dipyrrolidinobenzophenone and the appropriate aryl-lithium derivative, by dissolution in acetic acid and treatment with a saturated solution of sodium perchlorate.[7]

4,4′-*Dipyrrolidinobenzophenone.*—A mixture of 4,4′-dichlorobenzophenone (10 g, 0.04 mol), pyrrolidine (17.1 g, 0.24 mol), and tetramethylene sulphone (50 cm^3) was boiled under reflux for 24 h. The cooled reaction mixture was poured into ice–water (2 dm^3). The solid was collected, triturated with ether, and recrystallised from toluene to give the *ketone* (69%), m.p. 262—264 °C, as yellow crystals (Found: C, 78.5; H, 7.4; N, 8.7. $C_{21}H_{24}N_2O$ requires C, 78.7; H, 7.5; N, 8.7%).

4′,4″-*Dipyrrolidino*-3-*trifluoromethyltriphenylmethanol.*—A slurry of 4,4′-dipyrrolidinobenzophenone (2.9 g, 0.009 mol) in ether was added to 3-trifluoromethylphenyl-lithium [prepared from 3-bromotrifluoromethylbenzene (2.25 g, 0.01 mol) in ether (20 cm^3) and butyl-lithium (7.6 cm^3, 0.01 mol in hexane)]. After 3 h, the mixture was hydrolysed and work-up in the usual manner afforded the *dye-base* (28%), m.p. 120—121 °C [from light petroleum (b.p. 40—60 °C)] (Found: C, 72.4; H, 6.4; F, 12.0; N, 6.3. $C_{28}H_{29}F_3N_2O$ requires C, 72.1; H, 6.3; F, 12.2; N, 6.0%). 4′,4″-*Dipyrrolidino*-3-*trifluoromethyltriphenylmethyl perchlorate* was obtained as lustrous metallic blue crystals (Found: C, 60.9; H, 5.4; N, 5.0. $C_{28}H_{28}ClF_3N_2O_4$ requires C, 61.3; H, 5.1; N, 5.1%).

3-*Methyl*-4′,4″-*dipyrrolidinotriphenylmethanol* (42%), m.p. 144—146 °C after crystallisation from ethyl acetate–light petroleum (b.p. 80—100 °C), was similarly prepared from 3-methylphenyl-lithium (Found: C, 81.0; H, 7.9; N, 6.7. $C_{28}H_{32}N_2O$ requires C, 81.5; H, 7.8; N, 6.8%). The *perchlorate* was formed as lustrous metallic green crystals (Found: C, 67.2; H, 6.4; Cl, 7.7; N, 5.5. $C_{28}H_{31}ClN_2O_4$ requires C, 67.9; H, 6.3; Cl, 7.2; N, 5.7%).

3-*Bromo*-4′,4″-*dipyrrolidinotriphenylmethane* (59%), m.p. 143—145 °C from ethyl acetate–light petroleum (b.p. 60—80 °C) was prepared from 3-bromobenzaldehyde and *N*-phenylpyrrolidine[8] (Found: C, 70.6; H, 6.4; Br, 17.7; N, 6.0. $C_{27}H_{29}BrN_2$ requires C, 70.3; H, 6.3; Br, 17.3; N, 6.1%). Lustrous metallic green crystals of the *perchlorate* were obtained from ethyl acetate (Found: C, 57.5; H, 4.8; Br, 14.5; Cl, 6.5; N, 4.9. $C_{27}H_{28}BrClN_2O_4$ requires C, 57.9; H, 5.0; Br, 14.3; Cl, 6.3; N, 5.0%).

3-*Nitro*-4′,4″-*dipyrrolidinotriphenylmethane* (38%), m.p. 162 °C [from dichloromethane–light petroleum (b.p. 60—80 °C], was similarly obtained from 3-nitrobenzaldehyde (Found: C, 76.2; H, 6.6; N, 9.5. $C_{27}H_{29}N_3O_2$ requires C, 75.9; H, 6.8; N, 9.8%); *perchlorate*, lustrous metallic green crystals (Found: C, 61.6; H, 5.4; Cl, 6.5; N, 7.7. $C_{27}H_{28}ClN_3O_6$ requires C, 61.7; H, 5.4; Cl, 6.7; N, 8.0%).

Results and Discussion

The observations made for the parent dye Pyrrolidine Green (PG^+)[1] with respect to Beer's law, the reversibility of the hydrolysis reactions, and the linearity of the $\log_e$ (absorbance) *versus* time plots were also found to apply to each of the dyes studied.

Equations (1)—(3) apply to each set of results. Values of k' at each OH^- concentration and temperature are given for each

$$\text{Rate} = k_1[PG^+][H_2O] + k_2[PG^+][OH^-] \quad (1)$$

$$\text{Rate} = k'[PG^+] \quad (2)$$

$$k' = k_1[H_2O] + k_2[OH^-] \quad (3)$$

Table 1. Effect of temperature on k_2 and ρ, together with thermodynamic activation parameters for the reaction between dye cations and hydroxide ions

	k_2/dm^3 mol^{-1} s^{-1}					$\Delta H^\ddagger$/kJ mol^{-1}	$\Delta S^\ddagger$/J K^{-1} mol^{-1}
Substituent	293.2 K	298.2 K*	303.2 K	308.2 K	313.2 K		
H	0.364 ±0.003	0.54 (2.12) ±0.02 (±0.07)	0.862 ±0.007	1.25 ±0.02	1.78 ±0.01	57.9 ±0.9	−56 ±3
3-CH_3	0.299 ±0.004	0.491 (1.46) ±0.008 (±0.04)	0.78 ±0.01	1.12 ±0.02	1.63 ±0.03	62 ±2	−42 ±6
3-Br	0.536 ±0.006	0.825 (3.7) ±0.006 (±0.1)	1.32 ±0.03	1.89 ±0.04	2.65 ±0.02	58.5 ±0.9	−51 ±3
3-CF_3	0.72 ±0.01	1.08 (5.2) ±0.02 (±0.2)	1.50 ±0.04	2.11 ±0.04	3.15 ±0.04	55 ±1	−66 ±4
3-NO_2	1.04 ±0.01	1.48 (11.2) ±0.02 (±0.1)	2.38 ±0.01	3.25 ±0.04	4.7 ±0.1	56 ±2	−53 ±7
Reaction constant ρ at given temperature	0.64 ±0.04	0.60 (1.11) ±0.03 (±0.07)	0.60 ±0.01	0.56 ±0.02	0.53 ±0.01		

* Values obtained in 44% acetone–water at 298.2 K in parentheses.

dye in Supplementary Publication No. SUP 56086 (6 pp.).* The values of k_2, $\Delta H^\ddagger$, and $\Delta S^\ddagger$, given in Table 1, were computed by the procedure described earlier.[1] The measured values of k_1 were all of the same order of magnitude as that of the parent dye. However, these values, being prone to large standard errors, do not show any systematic variations with substituent effects, and are therefore not tabulated.

A thorough and precise investigation of the effects of 3-substitution on the reactivity of Pyrrolidine Green was achieved by careful choice of substituents, in accordance with the suggestions of several workers.[9] Using a weighted least squares computer program,[10] a Hammett line was established at five temperatures. Values for the substituent constants, σ, were taken from the compilation of Charton.[11] The values of the reaction constant, ρ, at each temperature are given in Table 1. The observed decrease in ρ with increasing temperature was not evident during independent studies on derivatives of Brilliant Green[7] or Malachite Green,[12] although similar substituents were used. The value of 0.64 ± 0.04 obtained for ρ during this study can be compared with the results quoted for Brilliant Green (0.60 ± 0.07)[7] and Malachite Green (0.50 ± 0.02;[13] 0.63 ± 0.04;[12] 0.57[14]). As expected, the Pyrrolidine Green cation is shown to be stabilised by electron donation and destabilised by electron-withdrawing substituents, but the magnitude of ρ indicates that the reaction is relatively insensitive to substituent effects, implying only a small change in charge density at the central carbon atom of Pyrrolidine Green.

A value of 370 ± 70 K is obtained for the isokinetic temperature, β, from the slope of a $\Delta H^\ddagger$ *versus* $\Delta S^\ddagger$ plot, a figure which can be compared with 130 ± 30 K for some derivatives of Brilliant Green[7] and to 330 K for the Malachite Green series.[13] The implication that the hydrolysis of Pyrrolidine Green derivatives is under enthalpy control in the experimental range of temperatures whereas the hydrolysis of derivatives of Brilliant Green is under entropy control seems to be rather arbitrary[15] when examination of the data in Table 1 reveals that relative changes in $\Delta S^\ddagger$ are somewhat greater than those in $\Delta H^\ddagger$.

Exner[16] has presented several alternative methods for testing the existence of an isokinetic relationship and for the determination of β. The weighted least squares computer program based on the equations of Margerison[10] was applied both to plots of ρ *versus* $1/T$ and log $k_{313.2}$ *versus* log $k_{293.2}$ and gave values of β of 580 ± 70 and 460 ± 200 K, respectively.

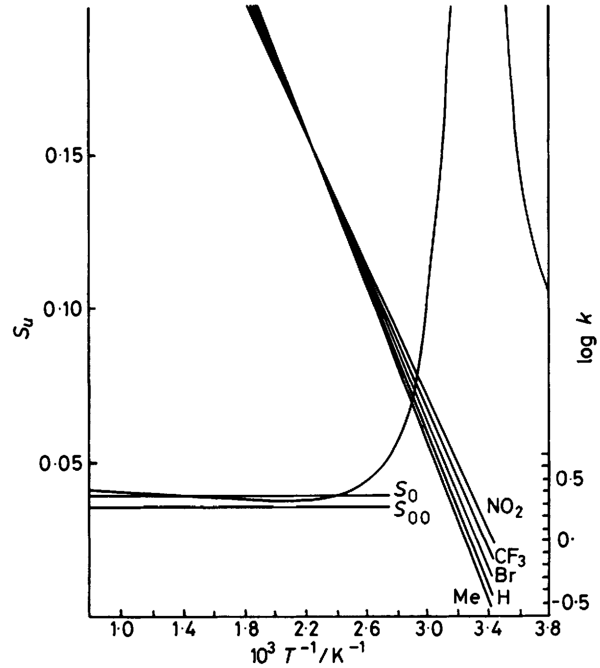


Figure 1. Isokinetic relationship for the reaction of some 3-substituted Pyrrolidine Greens with hydroxide ion

Arrhenius plots give the most general representation of the isokinetic relationship, since there should be a common point of intersection, representing β, in the log k *versus* $1/T$ plots. At β, each derivative should react at the same rate, whilst on the opposite side of β to the working temperature range the relative rates should be reversed. This phenomenon, although theoretically possible, is rarely observed in solution kinetics, since β is usually well removed from the working temperature range. However, a reversal of reactivity within a reaction series for the hydrolysis of some derivatives of Malachite Green was reported by Idlis and Ginsburg.[17]

Visible inspection of our results (Figure 1) indicated a common point of intersection in the Arrhenius plots and an estimate of 460 K was made for β. The equations of Exner[16]

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* For details of Supplementary Publications see Instructions for Authors in *J. Chem. Soc., Perkin Trans. 2*, 1985, Issue 1.

Table 2. Effects of variation in ionic strength on k_2 at 298.2 K

Substituent	k_2/dm^3 mol^{-1} s^{-1} at given ionic strength (mol dm^{-3})* 0.005 (0.1)	0.0075 (0.2)	0.01 (0.3)	0.025 (0.4)	0.05 (0.5)	Z_AZ_B
H	0.579 (0.414)	0.563 (0.353)	0.545 (0.315)	0.489 (0.296)	0.435 (0.269)	-0.81 ± 0.01
3-Me	0.511	0.502	0.478	0.444	0.394	-0.73 ± 0.04
3-Br	0.884	0.840	0.825	0.729	0.656	-0.83 ± 0.04
3-CF_3	1.18	1.14	1.09	0.958	0.856	-0.92 ± 0.04
3-NO_2	1.58	1.55	1.46	1.27	1.13	-0.98 ± 0.06

* Results obtained at higher ionic strength are in parentheses.

were used to compute a statistical test on the validity of the isokinetic relationship. The standard error S_u, obtained using the assumption that there is a common point of intersection, was determined as a function of $1/T$. The results are shown in Figure 1 and a close similarity to the curves produced by Exner is apparent. A comparison between the functions S_0, calculated from the minimum value of S_u and the appropriate number of degrees of freedom, and S_{00}, the standard error calculated without the restraint of a common point of intersection, leads to the conclusion that an isokinetic relationship exists to a confidence level of 93%, despite the fact that the value of β, 470 K, cannot be fixed more precisely than between the limits 610 and 430 K. This result can be taken as good evidence that each of the derivatives of Pyrrolidine Green is hydrolysed by a common mechanism. In addition, β is shown to be at an appreciably higher temperature than the working range, contrasting sharply with the work on Brilliant Green.[7]

The linear free energy relation study was repeated at 298.2 K using 44 w/w% acetone–water. Linearity of both the $\log_e$ (absorbance) *versus* time and k' *versus* $[OH^-]$ plots indicated that equations (1)—(3) still apply. These values of k' are also given in Supplementary Publication No. SUP 56086 and the values of k_2 are included in Table 1. The observed increase in the rate of reaction in the mixed solvent system is in accord with the work of Ingold,[18] who reasoned that reactions in which ionic charges disappear during formation of the transition state are expected to proceed faster in solvents of decreased polarity. The good Hammett correlations in both solvent systems indicated that the reaction mechanism is not influenced by changes in substituent and are also in agreement with the statement that σ values are not affected by the polarity of the solvent.[19] However, on changing to the mixed solvent system there is a large increase in the value of ρ, indicating a greater susceptibility of the reaction to substituent effects. Such a pronounced effect on ρ is generally observed for a change in solvent polarity.

The results obtained for the effect of added inert electrolyte on the aqueous system are given in Table 2. The k_2 values were obtained from the experimental k' values and the established rate law assuming k_1 to be independent of ionic strength. Below ionic strengths of 0.05 mol dm^{-3}, the Brønsted–Bjerrum equation (4) was applicable to each derivative. The rate of

$$\log k = \log k_0 + 1.02\, Z_AZ_B \sqrt{I} \qquad (4)$$

reaction decreased with increasing ionic strength, indicating the involvement of oppositely charged ions in the rate-determining step. The Z_AZ_B values were not equal to the expected value of -1.0 for singly charged ions of opposite sign, but they are in the same range as other results quoted for triphenylmethane dyes.[7,20,21] The scatter shown by the Z_AZ_B values for the various derivatives is not unlike that reported for derivatives of Brilliant Green.[7] It is of interest to note that no such scatter was observed for a series of substituted Malachite Greens, for which the Z_AZ_B values were all very close to -1.0.[12] When the ionic strength variations were extended to an upper limit of 0.5 mol dm^{-3} for the parent dye, deviations from the Brønsted–Bjerrum equation were evident. However, the results were found to fit the modified Debye–Hückel equation (5)[22]

$$\log k = \log k_0 + 1.02\, Z_AZ_B \frac{\sqrt{I}}{1 + \sqrt{I}} \qquad (5)$$

as shown in Figure 2. The change in Z_AZ_B value from -0.81 ± 0.01 to -0.91 ± 0.03 is also noteworthy.

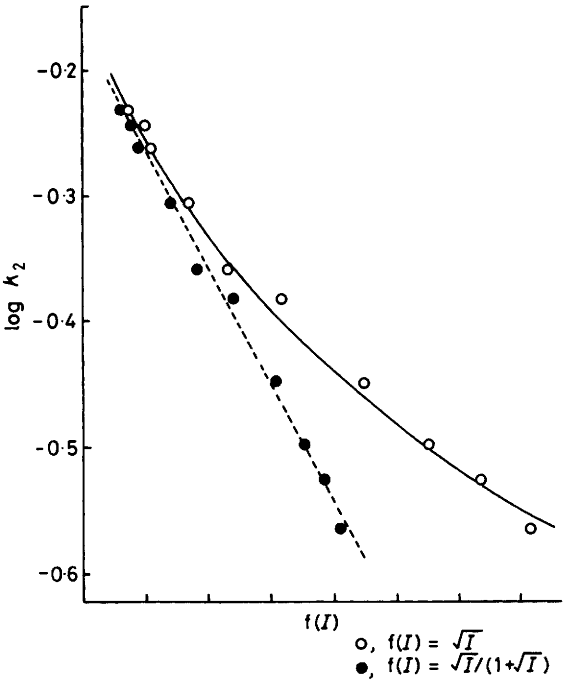

Figure 2. log k_2 as a function of I for Pyrrolidine Green at 298.2 K

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