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Studies of Azo Colors. XI.[1] The Diazo-coupling Reaction of Pyrroles

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Kinetic studies have been made of the coupling reaction of several diazonium salts with pyrrole, *N*-methylpyrrole, and *N*-ethoxycarbonylpyrrole. In the case of pyrrole, it was found, from the dependence of the apparent rate constant on the pH values, that the undissociated pyrrole reacted with diazonium salts in the pH range from 4.7 to 8.2, whereas in the pH region higher than 10.0 the reactive species was the conjugate base of pyrrole. The reactivity of the pyrrole anion was higher by a factor of 8 powers of ten than that of the undissociated pyrrole. The effects of the substituents of diazonium salts on the reaction rates were also investigated. The ρ-values (4.3—4.6) obtained in the Hammett plots were practically the same as those of diazo-coupling reactions which involve ordinary aromatic amines as coupling components.

Normally, diazo-coupling reactions take place between diazonium salts and substituted aromatic hydrocarbons, especially phenols and aromatic amines. The mechanisms and the structural effects of these reactions have been studied kinetically.[2]

Heterocyclic compounds, such as pyrrole,[3,4] indole,[5] imidazole,[6] and indazole,[7] have also long been known to react with diazonium salts to form azo compounds. Although the kinetic studies of some of these reactions have been carried out,[8,9] no detailed information on their mechanism and reactivity has yet been reported. In this paper, we wish to report the kinetics of the reactions of pyrroles with diazonium salts.

Results and Discussion

Brown and his co-workers[8] investigated the kinetics of the reaction of imidazole with diazonium salts. They found that the reaction of the diazonium ion with the imidazole anion formed by the ionization of the N–H bond was the rate-determining step. On the other hand, in the reaction of indole with diazonium salts, Binks and his co-worker[9] suggested that the undissociated indole was the reactive species.

Pyrrole is known to react with a diazonium salt, preferentially at the 2-position in a neutral solution, to form a monoazo compound, and to form a 2,5-bisazo compound in an alkaline solution.[3] However, it was confirmed by thin-layer chromatography that only a monoazo compound was obtained under our kinetic conditions, as will be described below.

Kinetic experiments have been carried out on the reactions of diazonium salts with 50 to 100 as many pyrroles in an aqueous buffer solution; the apparent rate constants (k') were calculated from Eq. (1), where E_t and E_∞ are the optical densities of the azo-compound at time t and at infinity respectively.

$$k't = \ln \frac{E_\infty}{E_\infty - E_t} \qquad (1)$$

In each kinetic run, an increase in the optical density of the azo-compound obeyed good pseudo-first-order kinetics. The reactions also showed a first-order dependence on the concentration of pyrrole. The dependences of the rate constants (k') on the pH values are listed in Tables 1, 2, and 3. In the pH range treated in Tables 1, 2, and 3, the diazonium salts are considered to exist practically as diazonium ions.[10] In the case of pyrrole, it has become apparent that the rate constant increases with increases in the pH values in the alkaline region. For example, in the reaction of pyrrole with *p*-methoxybenzenediazonium salt (Table 1) or benzenediazonium salt (Table 2), the reaction rate is independent of the pH values in

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TABLE 1. DEPENDENCE OF THE RATE CONSTANT (k') FOR THE REACTION OF PYRROLE WITH p-METHOXYBENZENEDIAZONIUM SALT ON pH AT 20°C (Pyrrole 4×10^{-3} mol/l; Diazonium salt 4×10^{-5} mol/l)

pH	4.69	6.01	5.89	6.31	7.11	7.49
k' (min^{-1})	0.0491	0.0472	0.0548	0.0570	0.0642	0.0617
k_2 (l mol^{-1} min^{-1})	1.23×10^1	1.18×10^1	1.38×10^1	1.43×10^1	1.61×10^1	1.54×10^1

pH	8.21	8.97	9.27	9.38	10.07	10.30	10.51	10.90
k' (min^{-1})	0.0672	0.118	0.172	0.201	0.532	0.861	1.33	3.48
k_2 (l mol^{-1} min^{-1})	1.68×10^1	—	—	—	—	3.49×10^9 (2.47×10^{-10})[a]	3.33×10^9 (4.00×10^{-10})	3.55×10^9 (9.84×10^{-10})

a) Values in parentheses are the concentration of pyrrole anion under experimental conditions.

TABLE 2. DEPENDENCE OF THE RATE CONSTANT (k') FOR THE REACTION OF PYRROLE WITH BENZENEDIAZONIUM SALT ON pH AT 20°C (Pyrrole 4×10^{-3} mol/l; Diazonium salt 4×10^{-5} mol/l)

pH	5.01	6.31	7.11	8.21	9.27	10.30
k' (min^{-1})	1.32	1.48	1.63	1.80	3.51	20.8

TABLE 3. DEPENDENCE OF THE RATE CONSTANT (k') FOR THE REACTION OF N-METHYLPYRROLE WITH p-METHYLBENZENEDIAZONIUM SALT ON pH AT 20°C (Pyrrole 4×10^{-3} mol/l; Diazonium salt 4×10^{-5} mol/l)

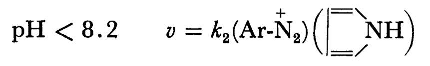
pH	5.10	5.79	6.30	6.30	8.13	10.13
k' (min^{-1})	0.741	0.778	0.944	0.970	1.04	1.26

TABLE 4. BASE CATALYSES IN THE REACTIONS OF SUBSTITUTED BENZENEDIAZONIUM SALT WITH PYRROLES AT 20°C (Pyrrole 4×10^{-3}; Diazonium salt 4×10^{-5})

Pyrroles	Substituents	pH	Pyridine concn. (mol/l)	k' (min^{-1})
Pyrrole	p-OCH$_3$	6.3	0.0	0.0570
			0.1	0.0672
			0.2	0.0749
			0.4	0.0890
			0.6	0.104
Pyrrole	H	10.6	0.0	1.48
			0.1	1.72
			0.2	1.78
			0.4	2.00
			0.6	2.16
N-Methylpyrrole	p-CH$_3$	6.3	0.0	0.944
			0.1	1.03
			0.2	1.13
			0.4	1.30
			0.6	1.49

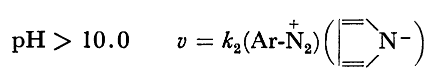
the pH range from 4.7 to 8.2; there is a slight dependence of k' on the pH values in the same range, which will be discussed later. However, the rate constant increased considerably when the pH value rose above 9.0.

The pK_a values of the pyrrole cation and pyrrole have been known to be 0.4[11] and 17.55[12] respectively. Therefore, pyrrole does not substantially dissociate in the pH range from 4.7 to 8.2. Thus, the fact that the reaction rate is independent of the pH may be explained by assuming that the undissociated pyrrole reacts with the diazonium salts (Eq. 2):



$$\mathrm{pH} < 8.2 \qquad v = k_2(\mathrm{Ar}\text{-}\overset{+}{\mathrm{N}}_2)\left(\ \mathrm{NH}\right) \qquad (2)$$

On the other hand, the reactive species is likely to be the pyrrole anion in an alkaline solution (Eq. 3), because the slope of the line between the log k' and pH values is close to unity in the pH region above pH 10.0. Furthermore, the observation that the reaction rates of N-methylpyrrole are essentially independent of the pH values, even in the alkaline region, supports the view mentioned above.



$$\mathrm{pH} > 10.0 \qquad v = k_2(\mathrm{Ar}\text{-}\overset{+}{\mathrm{N}}_2)\left(\ \mathrm{N}^-\right) \qquad (3)$$

Therefore, the second-order rate constants (k_2) were obtained according to Eq. (2) or (3) by dividing the first-order rate constants (k') by the undissociated pyrrole concentration or by the pyrrole anion concentration respectively. The results for the reaction of pyrrole with p-methoxybenzenediazonium salt are given in Table 1.

As can be seen from Table 1, the second-order rate constants (k_2) thus obtained are independent of the pH values of the medium, even in the alkaline region, suggesting that the application of Eq. (3) is reasonable. The pyrrole anion reacted faster by a factor of some 8 powers of ten than the undissociated pyrrole. The difference between the reactivities of these two species is similar to that observed between the reactivities of the naphthol and the naphtholate ion.[13] The reactivity of the pyrrole anion is greater by a factor of 5 orders than that of the naphtholate ion.[1]

It has been well known that some diazo-coupling reactions are accelerated by a base such as pyridine,[2] which acts as a proton acceptor from the intermediate of the substitution reaction. In order to confirm the base catalysis in the present study, the rate constants in the presence of the base (pyridine) have been measured. The results are given in Table 4. From these results, it can be seen that the reactions of pyrrole (pH 6.3), the pyrrole anion (pH 10.6), and N-methyl-

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TABLE 5. RATE CONSTANTS (k_2) FOR THE REACTIONS OF PYRROLES WITH SUBSTITUTED BENZENEDIAZONIUM SALT AT pH 6.3 (20°C)

Pyrrole	Substituent	k_2 ($\mathrm{l\,mol^{-1}\,min^{-1}}$)
Pyrrole	p-OCH_3	1.43×10^1
	p-CH_3	6.65×10^1
	m-CH_3	1.77×10^2
	H	3.70×10^2
	m-OCH	8.85×10^2
N-Methylpyrrole	p-OCH_3	5.08×10^1
	p-CH_3	2.36×10^2
	m-CH_3	5.85×10^2
	H	1.03×10^3
	m-OCH_3	2.46×10^3
N-ethoxycarbonylpyrrole	p-CH_3	4.79
	m-CH_3	1.61×10^1
	H	2.92×10^1
	m-OCH_3	9.15×10^1
	p-Cl	3.58×10^2

pyrrole were slightly catalyzed by the base. As has been described previously, in our experiments the rate measurements were performed in buffer solutions; the buffer reagent may be assumed to act also as a base in these cases. Therefore, the slight dependence of k' on the pH values in the pH range from 4.7 to 8.2 may be ascribed to the difference in the catalytic actions of buffer solutions.

In the cases of pyrrole, N-methylpyrrole, and N-ethoxycarbonylpyrrole, the influence of substituents in the diazonium salts on the rate constants was also investigated (Table 5). The results may be expressed by the following Hammett equations*[20]:

Pyrrole $\log k_2 = 4.63\sigma + 2.51$ $r=0.992$

N-Methylpyrrole $\log k_2 = 4.28\sigma + 2.99$ $r=0.986$

N-Ethoxycarbonylpyrrole $\log k_2 = 4.64\sigma + 1.48$ $r=0.985$

It can be seen from these results that the influence of the N-substituents in pyrrole on the reaction constant is small and that these ρ-values are similar to those in the coupling reactions of diazonium salts with ordinary aromatic amines, such as N,N-dimethylaniline (ρ; 4.34)[15] and 1-naphthylamine (ρ; 4.94).[15]

Experimental

Materials. The N-ethoxycarbonylpyrrole was prepared according to the method of Ciamician[16] from ethyl chloroformate and potassium salt of pyrrole. The commercial pyrrole, N-methylpyrrole, and aromatic amines used as diazo components were purified by distillation or by recrystallization prior to use. Their purities were checked by means of their physical constants and by gas-liquid chromatography.

Kinetic Measurements. The procedure was essentially the same as that described in an earlier paper.[17] The kinetic measurements were carried out in aqueous buffer solutions at 20 °C and at a constant ionic strength (0.04). Kinetic measurements in the presence of pyridine were carried out at a constant pH (6.3 or 10.3) according to the procedure of Zollinger *et al.*[8]

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