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Studies of Organic Peroxides. VIII. The Reaction of Benzoyl Peroxide with 5, 5′-Indigo-disulfonic Acid*[1]

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The reaction of benzoyl peroxide with 5, 5′-indigo-disulfonic acid was studied in ethanol. The effect of the *p*, *p*′-substituents of benzoyl peroxide on the reaction rate was investigated. It was found that the reaction is a bimolecular process. Either electron-attracting substituents or electron-releasing substituents promote the reaction. This was interpreted by means of the multicenter mechanism. The electron absorption spectra of the reaction mixture showed the formation of a reasonably stable complex in ethanol. This complex is decomposed by water to 5-isatinsulfonic acid and 5, 5′-indigo-disulfonic acid.

The reactions of benzoyl peroxide with secondary amines have been investigated extensively, and the main products of the reactions are well known.[1,2] The most likely mechanism of the reaction was proposed by Denney and Denney[3] after a study using benzoyl peroxide labeled with oxygen-18 in carbonyl oxygens. It involves a nucleophilic attack by the amine on the peroxide to give a pair of ions. On the other hand, kinetic investigations have been undertaken concerning the solvent effects.[4,5] It has been suggested that aliphatic amines decompose the peroxide by an ionic mechanism, while aromatic amines decompose it homolytically. Thus there still remain some questions about the mechanisms of the reaction.

In the present investigation, the effect of the *p*, *p*′-substituents of benzoyl peroxide on the reaction rate was studied in order to elucidate this problem. In this work, 5, 5′-indigo-disulfonic acid was chosen as the secondary amine. Since this substance has a characteristic absorption in the visible region, the rate of the reaction was followed colorimetrically. Some investigations of the reaction products were also undertaken, and the mechanism of the reaction was considered.

Experimental

Materials. Benzoyl peroxide and substituted benzoyl peroxides, namely, bis-*p*-nitrobenzoyl, bis-*p*-chlorobenzoyl, bis-*p*-methoxybenzoyl and bis-*p*-methylbenzoyl peroxides, were prepared by the method reported previously.[6]

Ethanol was purified by the usual method. The water in ethanol was removed with great care.

5, 5′-Indigo-disulfonic acid was prepared as follows: Reagent-grade indigo carmine was dissolved in distilled water. After the solution had then been subjected to electrodialysis, the water was removed by evaporation and the residue was extracted with absolute ethanol. After the evaporation of the ethanol, 5, 5′-indigo-disulfonic acid was obtained.

A plot of the absorbance at 610 mμ against the 5, 5′-indigo-disulfonic acid concentration showed a slight downward discrepancy from Beer's law. Hence, the experimental calibration curve was used to determine its concentration in the reaction mixture.

Measurements of the Reaction Rate. Reactions were carried out at temperatures between 20 and 40°C, with a 5, 5′-indigo-disulfonic acid concentration of the order of 10^{-5} M and a peroxide concentration ranging from 10^{-2} to 10^{-4} M. A typical kinetic experiment was carried out as follows: A definite amount of peroxide was dissolved in ethanol (100 m*l*) in a three-necked flask with a condenser attached. The reaction was initiated by the addition of an ethanolic solution (10 m*l*) of 5, 5′-indigo-disulfonic acid. Oxygen-free carbon dioxide was bubbled through the reaction mixture for the purpose of stirring the solution. At specified times after the beginning of the reaction, aliquots of the reaction mixture were pipetted out from the flask and the absorbance at 610 mμ was measured by a photoelectric colorimeter.

Reaction Products. To a solution of 0.868 g of benzoyl peroxide in 600 m*l* of absolute ethanol, equimolar amounts (1.49 g) of 5, 5′-indigo-disulfonic aicd in the same solvent were added; the mixture was then allowed to stand at room temperature for 3 days.

The solution changed from blue to red-brown. The solution was then evaporated to dryness under reduced pressure, and a small amount of water was added to the residue. By the filtration of the mixture

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*[1] Presented in part at the 18th Annual Meeting of the Chemical Society of Japan, Osaka, April, 1965.

[1] S. Gambarjan, *Ber.*, **42**, 4003 (1909).

[2] S. Gambarjan, *ibid.*, **58**, 1775 (1926).

[3] D. B. Denney and D. Z. Denney, *J. Am. Chem. Soc.*, **82**, 1389 (1960).

[4] O. A. Chaltykyan, E. N. Atanasyan, A. A. Sarksyan and D. S. Gaibakyan, *Zhur. Fiz. Khim.*, **32**, 2601 (1958).

[5] O. A. Chaltykyan, E. N. Atanasyan, N. M. Beileryan and G. A. Marmaryan, *ibid.*, **33**, 36 (1959).

[6] S. Hasegawa, N. Nishimura, S. Mitsumoto and K. Yokoyama, This Bulletin, **36**, 522 (1963).

0.663 g of crude benzoic acid was isolated. From the filtrate 5-isatin-sulfonic acid β-semicarbazone was derived by the usual method (crude 1.01 g). This was recrystallized repeatedly from water to give yellow needles, mp higher than 320°C. The infrared spectra in the KBr disk were essentially identical with those of isatin-β-semicarbazone, but there were additional peaks at 1180 and 1030 cm^{-1} ($-SO_3H$).

Found: C, 32.07; H, 3.92; N, 16.69%. Calcd for $C_9H_8N_4O_5S(H_2O)_3$: C, 31.95; H, 4.17; N, 16.57%.

Results and Discussion

Reaction Kinetics. The rate of the disappearance of 5, 5′-indigo-disulfonic acid was much faster than that expected from the spontaneous decomposition of benzoyl peroxide. If the disappearance is due to spontaneous decomposition, it should be followed to the zeroth-order kinetics with relation to the amine, but this is not the case, as will be shown.

In order to determine the reaction order, logarithmic plots of the concentration of 5, 5′-indigo-disulfonic acid against the time have been plotted for various initial concentrations of the two reactants (*cf.* Figs. 1 and 2).

It may be concluded from the linearity of the curves in these figures that this reaction is of the first order with respect to the amine.

If the slope of the curve, k', in Fig. 2 is plotted against the initial concentrations of benzoyl peroxide, one obtains a linear line passing through the origin of the coordinates, as is shown in Fig. 3.

It may be concluded from the above observations that the rate of this reaction is well represented by the empirical expression (1) in the region where the concentration of benzoyl peroxide is much greater than that of the amine.

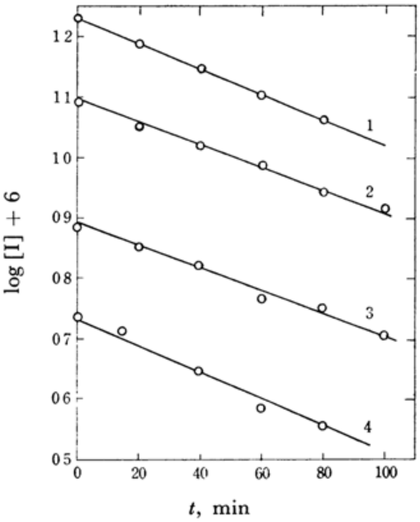

Fig. 1. Relation between log [I] and t at 35°C. $[I]_0 \times 10^5$: 1, 1.70; 2, 1.23; 3, 0.76; 4, 0.55 mol/l, $[BPO]_0$: 2.50×10^{-3} mol/l

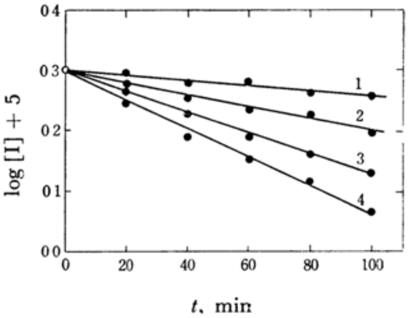

Fig. 2. Relation between log [I] and t at 25°C. $[BPO]_0 \times 10^3$: 1, 1.30; 2, 3.27; 3, 4.78; 4, 7.18 mol/l, $[I]_0$: 2.0×10^{-5} mol/l

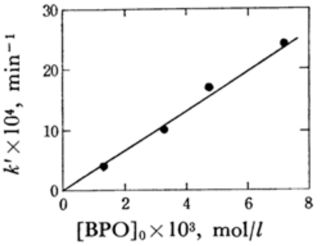

Fig. 3. Plots of k' against initial concentration of BPO.

$$-\frac{d[I]}{dt} = k[P][I] \tag{1}$$

where [P] and [I] denote the concentrations of benzoyl peroxide and the amine respectively, and where k is a constant.

Thus it could be said that the reaction of benzoyl peroxide with 5, 5′-indigo-disulfonic acid is of the first order with respect to each reactant.

Equation (1) also holds for the reactions with substituted peroxides.

It may be noted here that, in a supplementary experiment, no evolution of carbon dioxide was observed during the course of the reaction.

Substituent Effects. In Table 1 the values of k are listed for the reactions between symmetrically para-substituted benzoyl peroxide and 5, 5′-indigo-disulfonic acid at four temperatures. Using the data in Table 1, log k was plotted against $1/T$, as is shown in Fig. 4. Straight lines were drawn by means of the least-squares method. The estimated values of the enthalpy and entropy of activation are listed in Table 2, together with the values of Hammett's substituent constants.[7]

It is interesting to note that either electron-attracting substituents or electron-releasing substituents lower the values of both the enthalpy and the entropy of activation.

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[7] H. H. Jaffé, *Chem. Revs.*, **53**, 191 (1953).

TABLE 1. RATE CONSTANTS k* FOR SYMMETRICALLY PARA-SUBSTITUTED BENZOYL PEROXIDES-5, 5′-INDIGO-DISULFONIC ACID REACTIONS IN ETHANOL

Substituent	25°C	30°C	35°C	40°C
Bis-*p*-methoxy	1.79 ± 0.06	2.61 ± 0.02	2.70 ± 0.03	4.14 ± 0.22
Bis-*p*-methyl	1.69 ± 0.03	1.99 ± 0.10	2.62 ± 0.10	3.12 ± 0.15
Unsubstituted	0.74 ± 0.02	1.14 ± 0.09	1.83 ± 0.07	3.02 ± 0.10
Bis-*p*-chloro	3.07 ± 0.08	3.54 ± 0.06	6.00 ± 0.03	9.27 ± 0.41
Bis-*p*-nitro	54.5 ± 1.1	—	66.5 ± 2.6	—

* Average value in $l\,\text{mol}^{-1}\,\text{min}^{-1}$

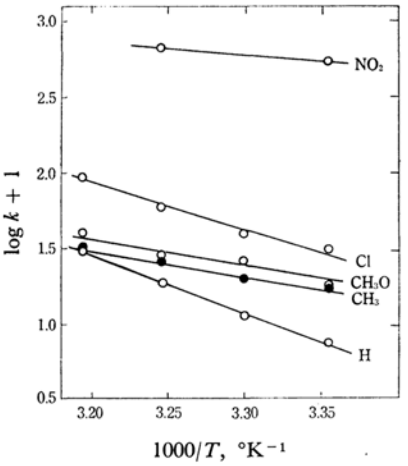

Fig. 4. Arrhenius plot of $\log k$ against $1/T$.

TABLE 2.* ENTHALPY AND ENTROPY OF ACTIVATION FOR REACTION OF SUBSTITUTED BENZOYL PEROXIDE WITH 5, 5′-INDIGO-DISULFONIC ACID IN ETHANOL

Substituent	$\Delta H^{\ddagger}$ kcal/mol	$\Delta S^{\ddagger}$ e. u. (298°K)	σ
CH_3O-	7.3 ± 0.6	-41.4 ± 2.1	-0.268
CH_3-	7.3 ± 0.8	-41.1 ± 2.6	-0.170
H-	16.8 ± 0.9	-10.8 ± 2.9	0
Cl-	14.0 ± 0.5	-17.5 ± 1.6	0.227
NO_2-	3.5 ± 0.8	-46.9 ± 2.7	0.778

* Standard deviations of $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were calculated based on the values of k at 25 and 35°C.

The value of $\Delta S^{\ddagger} \cong -10$ e.u., for unsubstituted peroxide corresponds to the formation of a new bond in the activated complex.⁶⁾ Highly negative values for substituted peroxides correspond to the formation of an activated complex with an ionic character. In such a case a great diminution of the activation entropy would be caused by solvation.⁸⁾

In Fig. 5, $\log(k/k_0)$ at 25°C is plotted against σ, where k is the rate constant for substituted benzoyl peroxide and where k_0 refers to the unsubstituted peroxide. Hammett's relationship gives two straight lines; one correlates the electronegative substituents, and the other, the electropositive substituents. It may be noted that both electron-releasing and electron-attracting substituents facilitate the reaction. In such a situation, the linear enthalpy-entropy relationship corresponding to each Hammett's relationship can be expected to hold.

In Fig. 6, the enthalpy of activation, $\Delta H^{\ddagger}$, is plotted against the entropy of activation, $\Delta S^{\ddagger}$. Allowing for the standard deviation (indicated in Table 2), one might conclude that these five points fall on a straight line. However, from the above discussion, it may be more reasonable to

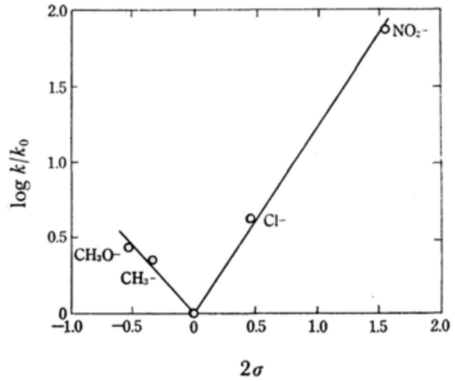

Fig. 5. Hammett's plot of $\log(k/k_0)$ against σ.

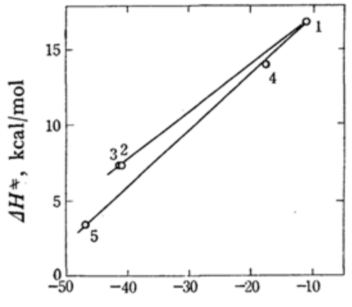

Fig. 6. Relationship between $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$.
Substituent: 1, H; 2, CH_3O; 3, CH_3;
4, Cl; 5, NO_2

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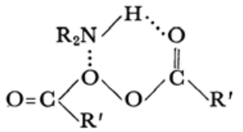
8) V. Gold, "Advances in Physical Organic Chemistry," Academic Press, London (1963), p. 11.

conclude that there are two linear lines, as in Fig. 6, and that there are two series of reactions. The isokinetic temperatures of these reaction series are calculated to be 320 and 380°K respectively, well above the experimental temperatures. Therefore, these reactions are governed mainly by enthalpy factors, and the relative reactivities are greater, the smaller the enthalpy of the activations are.

On the reactions between phenols and benzoyl peroxide, Walling and Hodgdon⁹⁾ have shown that not only electron-supplying *p*-substituents of phenol but also electron-attracting *p*-substituents accelerate the reaction. They examined the reaction in detail and postulated a four-center mechanism for this reaction. According to their mechanism, the abnormal substituents effects (no simple Hammett's relationship) can be well explained. On the other hand, Huisgen and Bayerlein¹⁰⁾ have also assumed a multicenter mechanism for the reactions of secondary amines with benzoyl peroxide on the basis of the fact that secondary amines react more rapidly than tertiary amines.

It could be reasonably assumed that 5, 5′-indigo-disulfonic acid, possessing a NH-group, probably reacts with benzoyl peroxide to form an activated complex with the structure depicted below:



If we assume such a multicenter mechanism, our results can be well understood. That is, electronegative substituents would decrease the electron density on the peroxide oxygen atom and make the nucleophilic attack of the nitrogen atom of amine on the peroxide oxygen atom easier. This would result in the decrease in the $\Delta H^{\neq}$ value. In this case electron transfer would play an important role. On the other hand, electropositive substituents would increase the electron density on carbonyl oxygen of peroxide and facilitate the interaction of this oxygen atom with the hydrogen atom of amine. This would also lower the $\Delta H^{\neq}$ value. In this case proton transfer would play a predominant role in the reaction. Thus the reaction would be accelerated by both electronegative and electropositive substituents.

However, not much can be said about the general applicability of this mechanism to the reaction between benzoyl peroxide and secondary amines, because the reaction products differ in type from those of usual secondary amines, as will be discussed below.

Reaction Products. After the completion of the reaction, a portion of the sample was pipetted out and diluted with absolute ethanol in order to investigate the ultraviolet absorption spectra of the reaction mixture. The absorption spectra are illustrated in Fig. 7. In addition to a peak at 237 mμ, which is probably due to benzoic acid, an absorption ranging from 250 to 270 mμ was observed. This compound is fairly stable in absolute ethanol, but it could not be isolated because it is very unstable in the presence of water. If the solution is evaporated to dryness under reduced pressure and a small amount of water is added to the residue, the compound is decomposed to 5-isatin-sulfonic acid and 5, 5′-indigo-disulfonic acid.

The occurrence of 5, 5′-indigo-disulfonic acid in this stage means that the compound still maintains an indigo-like structure. Wieland¹¹⁾ has reported that dehydroindigo is decomposed with water to isatin and indigo. Although the ultraviolet absorption spectra of the compound apparently differed from those of dehydroindigo prepared by the method of Kalb,¹²⁾ it may reasonably be assumed that this is a complex which is decomposed with water to 5-isatin-sulfonic acid (V) and 5, 5′-indigo-disulfonic acid (I) via 5,5′-dehydroindigo-disulfonic acid (IV).

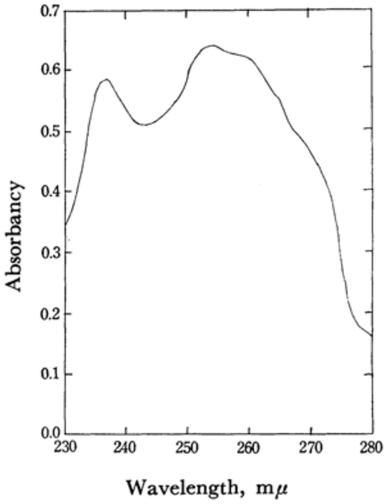


Fig. 7. Absorption spectra of reaction mixture in ethanol.

The absorption spectra of 5-isatin-sulfonic acid were very similar to those of isatin ($\lambda_{max}^{H_2O}$, 244 mμ).

5-Isatin-sulfonic acid was identified by the derivation of semicarbazone. The rather good

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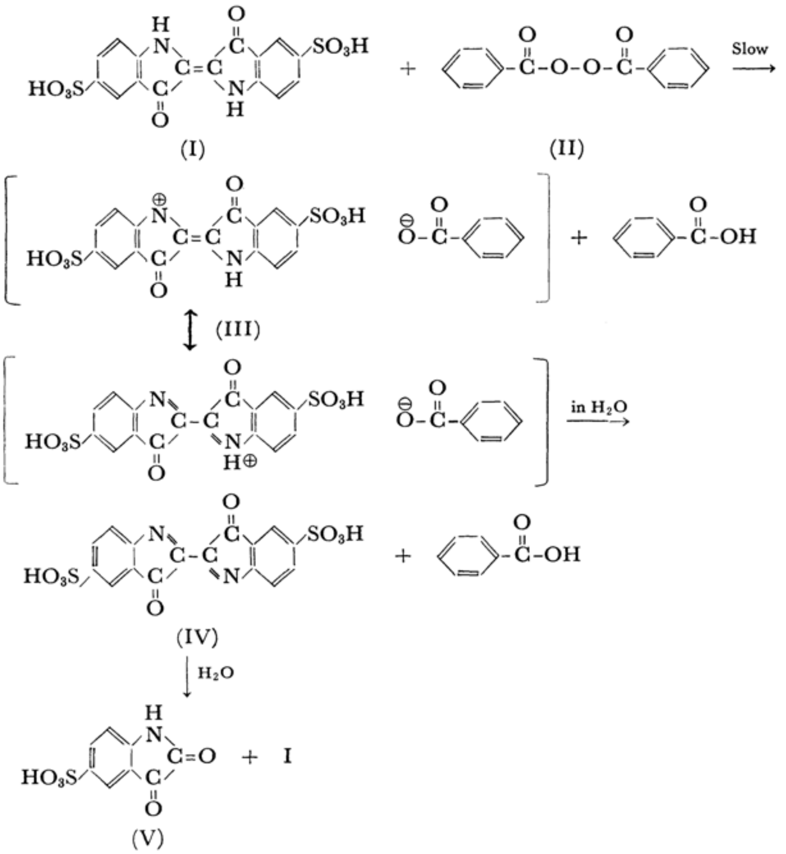
9) C. Walling and R. B. Hodgdon, Jr., *J. Am. Chem. Soc.*, **80**, 228 (1958).

10) R. Huisgen and F. Bayerlein, *Ann.*, **630**, 138 (1960).

11) H. Wieland, *Ber.*, **54**, 2353 (1921).

12) L. Kalb, *ibid.*, **42**, 3642 (1909).



yield of 5-isatin-sulfonic acid (44% as a semicarbazone) suggests that it is formed by the main reaction. 5-Isatin-sulfonic acid was also produced by the reactions with substituted peroxides.

It is interesting to note that one of the main reaction products is 5-isatin-sulfonic acid, whereas other secondary amines generally give *O*-benzoyl hydroxyl amines or *N*-benzoyl-*o*-hydroxy phenyl amines.[1-3,13]

The reaction mixture had an odor characteristic of ethyl benzoate, but the amount of ethyl benzoate was too small to be isolated.

On the basis of these results, the main reactions may be presented as shown in Scheme 1.

The first step of the reaction is a bimolecular reaction between 5, 5′-indigo-disulfonic acid (I) and benzoyl peroxide (II). This seems to be a rate-determining step, where the multicenter mechanism may be assumed. The reaction gives a complex (III) which decomposes in the presence of water.

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13) J. T. Edward, *J. Chem. Soc.*, **1954**, 1464.