Kinetics of the Oxidative Coupling of Benzyl Cyanides by Halogen or Hypohalite

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Oxidative coupling of benzyl cyanides by halogen or hypohalite, giving α,α'-dicyanostilbenes, has been studied kinetically by means of uv spectrophotometry in pure and aqueous dioxane containing a strong base. The rate is independent of the halogen or hypohalite concentration and expressed as $v = k[PhCH_2CN][base]$. The effect of ring substituent on the reaction of benzyl cyanides with I_2–NaOH in 50% aqueous dioxane at 25° gives a ρ value of +3.67. A mechanism is postulated, which involves a rate-determining α-proton abstraction from benzyl cyanide followed by a rapid hypohalite attack to give α-halobenzyl cyanide. The subsequent steps may be (A) the formation of 2,3-diphenylsuccinonitrile by the reaction of α-halobenzyl cyanide with the carbanion from benzyl cyanide and/or (B) the condensation of two molecules of α-halobenzyl cyanide. The rate law for the reaction of 2,3-diphenylsuccinonitrile with *tert*-butyl hyperchlorite in the presence of a base to form α,α'-dicyanostilbene is expressed as $v = k[PhCH(CN)CH(CN)Ph][base][t\text{-}BuOCl]$, which supports a mechanism involving the deprotonation of the succinonitrile by a base followed by a rate-determining hypohalite attack and then the elimination of hydrogen halide to form α,α'-dicyanostilbene. The rate law for the reaction of α-chlorobenzyl cyanide with a base to form dicyanostilbene is expressed as $v = k[PhCHClCN]^2[base]^2$ and suggests a mechanism which involves the deprotonation of α-chlorobenzyl cyanide followed by a nucleophilic attack of the formed carbanion on α-chlorobenzyl cyanide to form 2-chloro-2,3-diphenylsuccinonitrile and a subsequent elimination of hydrogen chloride.

The reaction of oxidative coupling of benzyl cyanide by iodine was originally found by Knövenagel and Chalanay in 1892.[1] Since then the reaction has been applied in organic syntheses.[2,3]

$$\underset{\mathbf{1}}{2PhCH_2N} + 2I_2 + 4RONa \longrightarrow \underset{\mathbf{2}}{PhC(CN){=}C(CN)Ph} + 4ROH + 4NaI$$

The mechanism of this reaction was little studied. Knövenagel speculated this reaction to involve the formation of diphenylsuccinonitrile with little evidence. Recently, Shipp[4,5] has postulated that the mechanism for the reaction of 2,4,6-trinitrotoluene with sodium hypochlorite, giving 2,2′,4,4′,6,6′-hexanitrostilbene, involves the formation of trinitrobenzyl anion followed by a "positive halogen" attack to afford trinitrobenzyl halide, which then react with each other by a displacement–elimination mechanism to form the product.

The condensation of two molecules of α-halobenzyl cyanides with bases and related reactions were studied by numerous investigators,[6-13] and three[14] mechanisms were postulated: (1) the carbene mechanism,[6-9] (2) the coupling of a carbonium ion with a carbanion followed by the elimination of hydrogen halide,[10] and (3) the nucleophilic displacement of substrate with carbanion followed by the elimination of hydrogen halide.[4,11,12] The kinetic studies[6,7] on these reactions favored the first mechanism, while the isolation of an intermediate such as 2-halo-2,3-diphenylsuccinonitrile suggested the second or third mechanism.[10,11]

The authors wished to clarify this obscurity and to find out a more reasonable mechanism for the reaction of benzyl cyanides with halogen or hypohalite in the presence of a base in dioxane. The present paper is a summary of our kinetic data obtained by the observation of formation of α,α'-dicyanostilbenes by means of uv spectrophotometry and a discussion on a probable mechanism for the reaction.

Results

Rate Law. The rate of the reaction of benzyl cyanide with *tert*-butyl hypochlorite or molecular iodine in the presence of a base to give α,α'-dicyanostilbene was measured in pure and aqueous dioxane at 22 or 25°; the kinetic data are listed in Tables I and II. The rate law is expressed as eq 1.

$$v = k[PhCH_2CN][base] \tag{1}$$

Table II shows the data for the reaction of benzyl cyanide with molecular iodine in the presence of NaOH. As shown in Table II, an increase of concentration of iodine decreases the rate, and the rate is proportional to $([NaOH] - 2[I_2])$.

$$v = k[PhCH_2CN](NaOH) - 2[I_2]) \tag{2}$$

As shown in Figure 1, the second-order plot is linear at least to 38% conversion.

The rate of the reaction of a probable intermediate 2,3-diphenylsuccinonitrile with *tert*-butyl hypochlorite in the presence of NaOH to form dicyanostilbene was measured in 50% aqueous dioxane at 25°, the data being listed in Table III. As apparent from the table, the rate law is expressed as eq 3.

$$v = k[PhCH(CN)CH(CN)Ph][base][t\text{-}BuOCl] \tag{3}$$

The rate of the reaction of α-chlorobenzyl cyanide with a strong organic base, diazabicycloundecene (DBU), and sodium *tert*-butoxide to form α,α'-dicyanostilbene was measured in dioxane at 25°. The data are listed in Table IV. When initial rate v_0 is plotted against $[PhCHClCN]_0^2$, $[DBU]_0^2$, and $[t\text{-}BuNa]_0^2$, straight lines are obtained (Figures 2–4), where subscript 0 denotes the time zero. In view of Figures 2 and 3, the rate law for the reaction of α-chlorobenzyl cyanide with DBU in dioxane is expressed as eq 4, and rate constants k' and k were calculated from the

$$v = [PhCHClCN]^2(k' + k[DBU]^2) \tag{4}$$

intercept and slope to be $k' = 4.30 \times 10^{-6}\ M^{-1}\ sec^{-1}$ and $k = 2.36 \times 10^{-2}\ M^{-3}\ sec^{-1}$ at 25°, respectively.

On the other hand, Figure 4 shows that the rate law for the reaction of α-chlorobenzyl cyanide with sodium *tert*-butoxide in dioxane is expressed as eq 5, and rate constant k is calculated to be $2.26 \times 10^5\ M^{-3}\ sec^{-1}$ at 25°.

Table I
Second-Order Rate Constants[a] for the Reaction of Benzyl Cyanide with a Mixture of t-BuOCl and t-BuONa in Dioxane at 22°

$[PhCH_2CN]_0$, 10^{-3} M	$[t\text{-BuONa}]_0$, 10^{-3} M	$[t\text{-BuOCl}]_0$, 10^{-3} M	10^4 k, M^{-1} sec^{-1}
2.29	18.8	2.95	7.75
2.29	15.0	2.95	8.06
2.29	11.3	2.95	7.58
2.29	7.52	2.95	7.44
2.29	5.64	2.95	7.59
2.29	3.77	2.95	7.82
2.29	15.0	2.36	8.05
2.29	15.0	1.48	7.97
2.87	15.0	2.95	8.08
1.72	15.0	2.95	7.96
1.15	15.0	2.95	8.23
0.866	15.0	2.95	8.01
0.571	15.0	2.95	7.90

[a] The constants were calculated by means of the equation $v = k[PhCH_2CN][t\text{-BuONa}]$.

Table II
Second-Order Rate Constants for the Reaction of Benzyl Cyanide with a Mixture of Molecular Iodine and NaOH in 50% Aqueous Dioxane at 25°

$[PhCH_2CN]_0$, 10^{-3} M	$[NaOH]_0$, 10^{-3} M	$[I_2]_0$, 10^{-3} M	10^4 k_{obsd},[a] M^{-1} sec^{-1}	10^4 k,[b] M^{-1} sec^{-1}
2.23	14.6	0.884	23.9	27.2
2.23	14.6	1.15	21.6	25.7
2.23	14.6	2.29	17.2	25.1
2.23	14.6	3.44	14.8	24.9

[a] The value calculated by the equation $v = k[PhCH_2CN]\cdot[NaOH]$. [b] The value calculated by the equation $v = k[PhCH_2CN]([NaOH] - 2[I_2])$.

Table III
Third-Order Rate Constants[a] for the Reaction of 2,3-Diphenylsuccinonitrile with a Mixture of t-BuOCl and NaOH in 50% Aqueous Dioxane at 25°

[PhCH(CN)CH(CN)Ph]$_0$, 10^{-3} M	$[NaOH]_0$, 10^{-3} M	$[t\text{-BuOCl}]_0$, 10^{-3} M	k, M^{-2} sec^{-1}
0.295	3.08	1.20	7.67
0.295	4.62	1.20	7.78
0.295	7.70	1.20	8.64
0.295	10.78	1.20	8.64
0.355	15.54	1.20	9.06
0.177	10.78	1.20	8.75
0.442	10.78	1.20	7.43
0.591	10.78	1.20	8.79
0.355	14.55	1.13	8.02
0.355	14.55	0.675	8.40
0.355	14.55	0.449	8.40
0.355	14.55	0.225	8.32

[a] The constants were calculated by means of the equation $v = k[PhCH(CN)CH(CN)Ph][NaOH][t\text{-BuOCl}]$.

$$v = k[PhCHClCN]^2[t\text{-BuONa}]^2 \qquad (5)$$

Substituent Effect. The rates of the reaction of some ring-substituted benzyl cyanides with a mixture of I_2 and NaOH were measured in 50% aqueous dioxane at 25° and are summarized in Table V.

The Hammett plot with σ gives a straight line (Figure 5), giving a ρ value of +3.67 with $r = 0.978$.

Solvent Effect. The rate of the reaction of benzyl cyanide with a mixture of I_2 and NaOH was measured at 25° in aqueous dioxane of various compositions and is shown in Table VI.

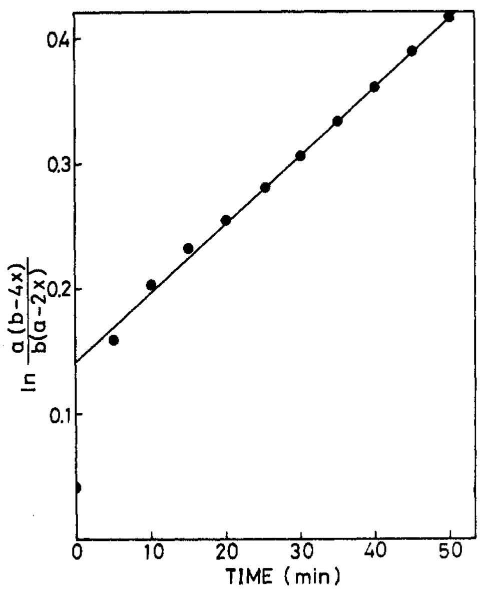


Figure 1. The second-order plot of ln $[a^2(b - 4x)/b(a - 2x)^2]$ against time for the reaction of benzyl cyanide with a mixture of iodine and sodium hydroxide in 75% aqueous dioxane at 22°: $a = [PhCH_2CN]_0 = 0.355 \times 10^{-3}$ M; $b = [NaOH]_0 - [I_2]_0 = 2.40 \times 10^{-3}$ M; $[I_2]_0 = 0.300 \times 10^{-3}$ M; x = [PhC(CN)=C(CN)Ph].

Table IV
Kinetic Data for the Reaction of α-Chlorobenzyl Cyanide with a Base (DBU[a] or t-BuONa) to Form α,α'-Dicyanostilbene in Dioxane at 25°

$[PhCHClCN]_0$, 10^{-3} M	$[Base]_0$, 10^{-3} M	v_0,[b] 10^{-9} M sec^{-1}
50.8	12.65[c]	20.4
40.6	12.65[c]	13.5
30.5	12.65[c]	7.98
20.6	12.65[c]	3.38
50.8	15.17[c]	27.0
50.8	27.0[c]	56.0
20.3	57.3[c]	25.6
20.3	54.1[c]	23.7
20.3	52.9[c]	22.0
20.3	45.0[c]	18.1
20.3	45.0	17.4
20.3	30.9[c]	10.1
20.3	27.0[c]	7.81
20.3	25.3[c]	6.68
20.3	18.0[c]	4.53
20.3	15.2[c]	4.28
0.762	1.06[d]	147
0.762	0.845[d]	90.9
0.762	0.635[d]	53.0
0.762	0.503[d]	36.2
0.762	0.442[d]	27.9

[a] Diazabicycloundecene. [b] Initial rate. [c] DBU was used as a base. [d] t-BuONa was used as a base.

Discussion

Initial Stage for Reaction of Benzyl Cyanide. Carbanion Formation. As to reaction of benzyl cyanide with *tert*-butyl hypochlorite, the rate eq 1 suggests that one molecule each of benzyl cyanide and a base should participate in the rate-determining step for the formation of α,α'-dicyanostilbene. In view of the rate eq 2 for the reaction of benzyl cyanide with a mixture of iodine and sodium hydroxide, most of the added molecular iodine is converted rapidly to hypoiodite and iodide ions under these conditions. In fact, an equilibrium constant[15] for eq 6 was measured to be 30-200 M^{-1} at 25° in water.[16]

$$I_2 + 2OH^- \rightleftharpoons OI^- + H_2O \qquad (6)$$

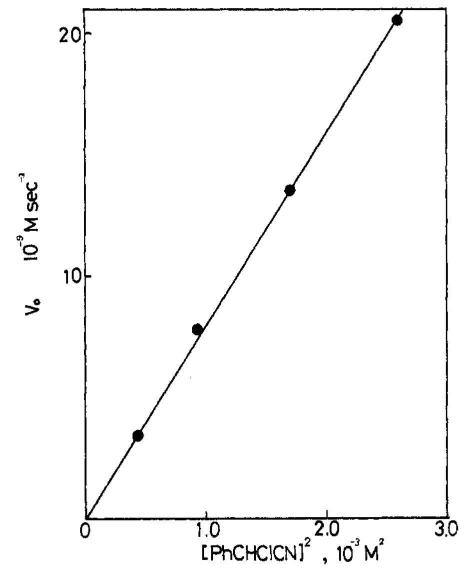


Figure 2. Plot of the initial rate v_0 *vs.* $[\mathrm{PhCHClCN}]_0^2$ for the reaction of α-chlorobenzyl cyanide with DBU at 25°. The concentration of DBU was 12.65×10^{-3} *M*.

When *tert*-butyl hypochlorite, for which an equilibrium such as eq 6 is not known, was used instead of iodine, the reaction of benzyl cyanide occurred similarly.

Therefore, it is likely that the active species for the reaction may not be molecular halogen, but the corresponding alkali hypohalite, which is known to afford a positive halogen.

The rate law and the ρ value of +3.67 suggests the rate-determining deprotonation of benzyl cyanide to give carbanion **3**. The intermediacy of the carbanion **3** has been postulated by Knövenagel[1] and Shipp.[4] The base-catalyzed hydrogen-deuterium isotope exchange of 2-phenyl-2-hydrohexafluoropropanes was considered to involve a rate-determining deprotonation, where a similar ρ value of 4.00 was observed.[17] An additional evidence for the existence of carbanion in the rate-determining step may be the observed solvent effect, *i.e.*, the rate is proportional to the volume fraction of water up to 50%. The increase of solvent polarity should favor the formation of carbanion. However, the solvolysis of α-halobenzyl cyanide occurs in a solvent of water content of over 50%; hence the proportionality of rate with water content is no longer observed.

Second Stage. Fate of Carbanion. The carbanion **3**, which is formed from benzyl cyanide, may react rapidly with alkyl or alkali hypohalite to give α-halobenzyl cyanide (**4**), where X is halogen (Scheme I).

Scheme I

$$\underset{\mathbf{1}}{\mathrm{PhCH_2CN}} + \mathrm{RO^-} \overset{\text{slow}}{\rightleftharpoons} \mathrm{Ph\bar{C}HCN} + \mathrm{ROH} \qquad (7)$$

$$\underset{\mathbf{3}}{\mathrm{Ph\bar{C}HCN}} + \mathrm{ROX} \xrightarrow{\text{fast}} \underset{\mathbf{4}}{\mathrm{PhCHXCN}} + \mathrm{RO^-} \qquad (8)$$

2,4,6-Trinitrobenzyl chloride corresponding to **4** was isolated by Shipp[4] in the reaction of 2,4,6-trinitrotoluene with sodium hypochlorite, where 2,2′,4,4′,6,6′-hexanitrostilbene was formed.

There may be two pathways for the formation of α,α′-dicyanostilbene from benzyl cyanide, *i.e.*, (A) the initial formation of 2,3-diphenylsuccinonitrile (**5**) by displacement of α-halobenzyl cyanide **4** with carbanion **3**, and (B) the condensation of α-chlorobenzyl cyanide with a base, which was postulated by Shipp.[4]

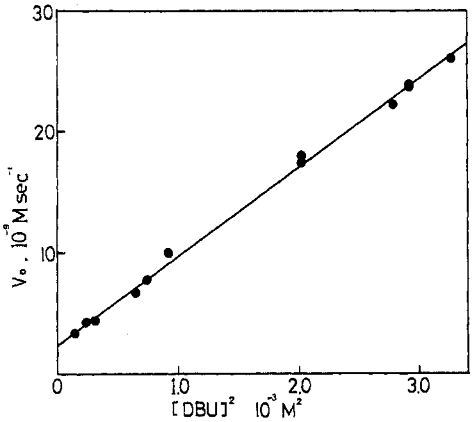


Figure 3. Plot of the initial rate v_0 *vs.* $[\mathrm{DBU}]_0^2$ for the reaction of α-chlorobenzyl cyanide with DBU at 25°. The concentration of α-chlorobenzyl cyanide was 2.36×10^{-3} *M*.

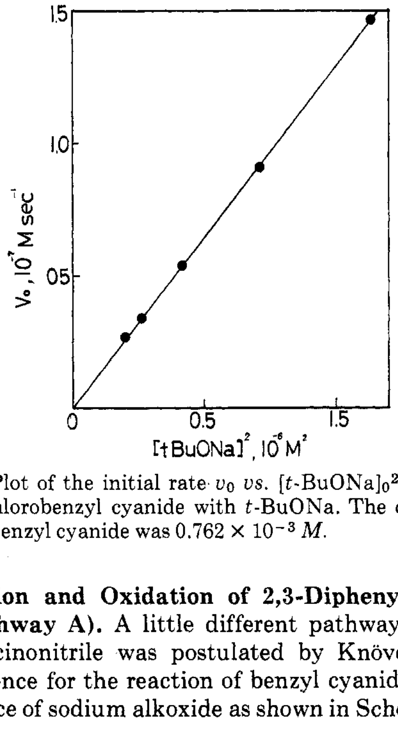


Figure 4. Plot of the initial rate v_0 *vs.* $[t\text{-BuONa}]_0^2$ for the reaction of α-chlorobenzyl cyanide with *t*-BuONa. The concentration of α-chlorobenzyl cyanide was 0.762×10^{-3} *M*.

Formation and Oxidation of 2,3-Diphenylsuccinonitrile (Pathway A). A little different pathway *via* 2,3-diphenylsuccinonitrile was postulated by Knövenagel with little evidence for the reaction of benzyl cyanide with I_2 in the presence of sodium alkoxide as shown in Scheme II.

Scheme II

$$\underset{\mathbf{1}}{\mathrm{2PhCH_2CN}} \xrightarrow{\mathrm{RO^-, -OH^-}} \underset{\mathbf{3}}{\mathrm{2Ph\bar{C}HCN}} \xrightarrow{\mathrm{I_2, -I^-}} \underset{\mathbf{5}}{\mathrm{PhCH(CN)CH(CN)Ph}} \qquad (9)$$

$$\mathbf{5} \xrightarrow{\mathrm{RO^-, -ROH}} \underset{\mathbf{6}}{\mathrm{Ph\bar{C}(CN)\bar{C}(CN)Ph}} \xrightarrow{\mathrm{I_2, -I^-}} \underset{\mathbf{2}}{\mathrm{PhC(CN){=}C(CN)Ph}} \qquad (10)$$

This was considered by analogy with the reaction of deoxybenzoin with a mixture of iodine and sodium alkoxide, giving bidesyl,[18] which, however, did not react further.

$$\mathrm{PhCH_2COPh} \xrightarrow{\mathrm{RO^-, I_2}} \mathrm{PhCH(COPh)CH(COPh)Ph} \not\rightarrow \mathrm{PhC(COPh){=}C(COPh)Ph}$$

However, Knövenagel's assumption[1] of participation of bianion **6** (Scheme II) is less probable.

2,3-Diphenylsuccinonitrile (**5**) was detected in our

Table V
Substituent Effect on the Reaction of Benzyl Cyanides with a Mixture of NaOH and Molecular Iodine in 50% Aqueous Dioxane at 25°

Registry no.	R^a	$10^4 k$, M^{-1} sec^{-1}	$k/k_0{}^b$	Log (k/k_0)
104-47-2	OMe	3.36	0.125	−0.903
2947-61-7	Me	5.46	0.204	−0.691
140-29-4	H	26.8	1	0
140-53-4	Cl	178.3	6.66	0.823

[a] Substituent of benzyl cyanides in the para position. [b] k_0 represents the rate constant of the reaction of unsubstituted benzyl cyanide. The rate constants were calculated by means of eq 2. ($[NaOH]_0 = 14.6 \times 10^{-3}$ M, $[I_2]_0 = 0.884 \times 10^{-3}$ M.)

Table VI
Solvent Effect on the Reaction of Benzyl Cyanide with a Mixture of NaOH and Molecular Iodine[a] in Aqueous Dioxane of Various Compositions at 25°

Dioxane, vol %	$10^4 k$, M^{-1} sec^{-1}
100	7.86
75	16.2
50	24.8
25	28.3

[a] $[PhCH_2CN]_0 = 2.23 \times 10^{-3}$ M, $[NaOH]_0 = 14.4 \times 10^{-3}$ M, $[I_2]_0 = 2.29 \times 10^{-3}$ M. The rate constants were calculated by means of eq 2.

hands by glc in the reaction of benzyl cyanide with a mixture of iodine and sodium methoxide at −75°. Furthermore, **5** was obtained by the reaction of benzyl cyanide with *tert*-butyl hypochlorite and excess sodium *tert*-butoxide in *tert*-butyl alcohol.

$$\underset{\mathbf{3}}{Ph\bar{C}HCN} + \underset{\mathbf{4}}{PhCHXCN} \longrightarrow \underset{\mathbf{5}}{PhCH(CN)CH(CN)Ph} + X^- \qquad (11)$$

The oxidation of isolated **5** with iodine in the presence of sodium methoxide gives α,α'-dicyanostilbene (**2**) in a yield of 95% in ether at 25° for 10 hr. Therefore, **5** should be an intermediate for the reaction of benzyl cyanide, which may be formed by nucleophilic displacement of α-halobenzyl cyanide (**4**) with carbanion **3**.

In view of the rate eq 3, it is likely that the reaction of hypohalite with the monoanion of succinonitrile (**7**) is a rate-determining step for the oxidation. We propose a mechanism expressed as Scheme III.

Scheme III

$$\underset{\mathbf{5}}{PhCH(CN)CH(CN)Ph} + RO^- \overset{\text{fast}}{\rightleftharpoons} \underset{\mathbf{7}}{Ph\bar{C}(CN)CH(CN)Ph} + ROH \qquad (12)$$

$$\underset{\mathbf{7}}{Ph\bar{C}(CN)CH(CN)Ph} + ROX \xrightarrow{\text{slow}} \underset{\mathbf{8}}{PhCX(CN)CH(CN)Ph'} + RO^- \qquad (13)$$

$$\underset{\mathbf{8}}{PhCX(CN)CH(CN)Ph} + RO^- \xrightarrow{\text{fast}} \underset{\mathbf{2}}{PhC(CN){=}C(CN)Ph} + ROH + X^- \qquad (14)$$

If the reaction of hypochlorite with monoanion **7** (eq 13) is a slow step, the rate equation should be first order in each of **5**, RO^-, and ROX, which is observed in the case of this reaction (eq 3). It is rather curious that eq 13 is rate determining, since the rate-determining step for the halogenation of benzyl cyanide has been known to be α-proton abstraction and the rate law of the halogenation of ketones such as haloform reaction is known to be independent of halogen concentration. The peculiar behavior of the present reaction may be ascribed to the steric hindrance for the attack of hypohalite on **7** owing to the crowded state of $PhC(CN)^-$ and the low nucleophilicity of carbanion **7** owing to the delocalization of negative charge by electron-withdrawing groups. Bidesyl[18] does not react further in the reaction of deoxybenzoin with a mixture of iodide and a base as previously described. This phenomenon is due to the similar steric hindrance for the attack of hypoidodite.

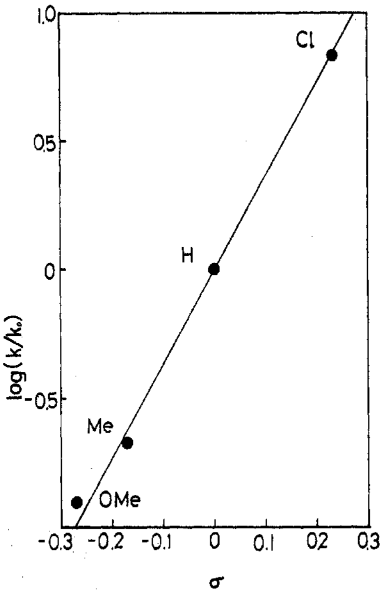


Figure 5. Hammett plot with σ for the reaction of benzyl cyanides with a mixture of iodine and NaOH in 50% aqueous dioxane at 25°.

Condensation of α-Chlorobenzyl Cyanide (Pathway B). Three probable mechanisms are conceivable for the reaction of two molecules of α-halobenzyl cyanide to form α,α'-dicyanostilbene, *i.e.*, (1) the carbene as an intermediate, (2) the coupling of carbonium ion with carbanion followed by the elimination of hydrogen halide, and (3) the nucleophilic displacement of the substrate with carbanion followed by the elimination of hydrogen halide.

The kinetic studies by Hanna and Swain showed that the reaction of 4-nitrobenzyl chloride[6] or 4-nitrobenzyldimethylsulfonium 4-toluenesulfonate[7] with sodium hydroxide to yield 4,4′-dinitrostilbene has the rate law $v = k[\text{substrate}][OH^-]$, and that 4-nitrobenzyl chloride reacts much (35–60 times) faster than benzyl chloride. They suggested for these bases the intermediate formation of 4-nitrophenylmethylene (Scheme IV).

Scheme IV

$$ArCH_2Cl + OH^- \overset{\text{fast}}{\rightleftharpoons} Ar\bar{C}HCl + H_2O \qquad (15)$$

$$Ar\bar{C}HCl \xrightarrow{\text{slow}} ArCH: + Cl^- \qquad (16)$$

$$2ArCH: \xrightarrow{\text{fast}} ArCH{=}CHAr \qquad (17)$$

However, they presented no direct evidence for the intermediacy of carbene. The isolation of the intermediates such as 2-halo-2,3-diphenylsuccinonitrile[10,11] rules out the carbene mechanism. Our kinetic observation can only be explained by Scheme V as follows.

Scheme V

$$\underset{4}{\mathrm{PhCHXCN}} + \mathrm{RO^-} \overset{\text{fast}}{\rightleftharpoons} \underset{9}{\mathrm{Ph\bar{C}XCN}} + \mathrm{ROH} \qquad (18)$$

$$\underset{9}{\mathrm{Ph\bar{C}XCN}} + \underset{4}{\mathrm{PhCHXCN}} \overset{\text{fast}}{\rightleftharpoons} \underset{8}{\mathrm{PhCX(CN)CH(CN)Ph}} + \mathrm{X^-} \qquad (19)$$

$$\underset{8}{\mathrm{PhCX(CN)CH(CN)Ph}} + \mathrm{RO^-} \xrightarrow{\text{slow}} \underset{2}{\mathrm{PhC(CN){=}C(CN)Ph}} + \mathrm{ROH} + \mathrm{X^-} \qquad (14)$$

If the deprotonation (eq 18) were a slow step, the rate law would be $v = k[\mathrm{PhCHXCN}][\text{base}]$, which is consistent with that observed by Hanna[6] and Swain.[7] Hanna's observation on the substituent effect favors this scheme because of an increase of the rate of deprotonation by a nitro group.

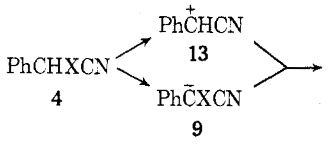
On the other hand, the presence of electron-attracting CN on the α position may increase the rate of deprotonation further; hence step 18 may be fast in the case of the reaction of α-chlorobenzyl cyanide. If the elimination of hydrogen halide is a slow step, the rate law should be second order in both the substrate and the base, as is the case (eq 4 and 5). This scheme can also explain the facile isolation of an intermediate such as 8 at an early stage of the reaction.[10,11]

The first term k' in eq 4, which is neglected in eq 5, $v = k[\mathrm{PhCHXCN}]^2[t\text{-BuONa}]^2$, because of the strong basicity of sodium *tert*-butoxide, may be some kinetic artifact.

The reaction of benzyl cyanide with excess *tert*-butyl hypochlorite in ether containing sodium methoxide at 25° was found to give α,α-dichlorobenzyl cyanide (**10**), whereas the reaction of benzyl cyanide with gaseous chlorine, which was bubbled into methanol containing sodium methoxide and a little water keeping the temperature below 50°, gave α,α-dichlorophenylacetamide (**11**) in a good yield. These results present evidences for the existence of carbanion 9 as an intermediate.

$$\underset{9}{\mathrm{Ph\bar{C}ClCN}} + \mathrm{ROCl} \longrightarrow \underset{10}{\mathrm{PhCCl_2CN}} \xrightarrow{\mathrm{H_2O}} \underset{11}{\mathrm{PhCCl_2CONH_2}} \qquad (20)$$

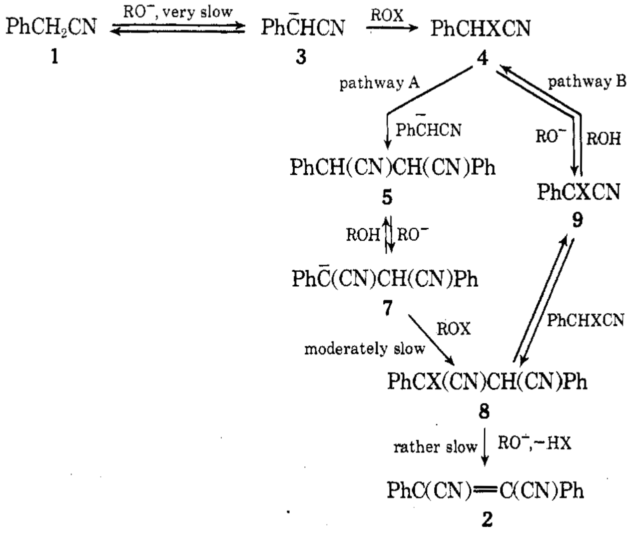
Hence, the presence of carbanion 9 as an intermediate in the reaction of α-halobenzyl cyanide with a base was confirmed, while there was no evidence for the carbonium ion. It seems impossible that carbonium ion is present under these basic conditions. Hence, the mechanism 12, suggested by Coe,[10] which involves coupling of carbonium ion 13 with carbanion 3 (eq 21), may be excluded.



$$\underset{8}{\mathrm{PhCX(CN)CH(CN)Ph}} \xrightarrow{-\mathrm{HX}} \underset{2}{\mathrm{PhC(CN){=}C(CN)Ph}} \qquad (21)$$

Overall Mechanism of Reaction of Benzyl Cyanide. In conclusion, the mechanism of the reaction of benzyl cyanide with a mixture of halogen or hypohalite and a base may be as follows. The abstraction of α proton from benzyl cyanide by a base occurs initially to give carbanion **3**, which then yields α-halobenzyl cyanide (**4**) by an attack with hypohalite (eq 7 and 8). Two pathways as shown below are conceivable for the subsequent steps (Scheme VI).

Scheme VI



Since the rate-determining step in pathway B is the last step (8 → 2) but that in pathway A is the former halogenation step (7 → 8), pathway B is faster than pathway A. However, since the concentration of 4 may be low compared with that of **1**, pathway A may be preferred to pathway B. This is evidenced by the fact that **5** is isolated in the reaction of benzyl cyanide with excess base and a small amount of hypohalite. Similarly, Shipp[4] showed that an equimolar amount of 2,4,6-trinitrotoluene and 2,4,6-trinitrobenzyl chloride give a 1:1 mixture of the hexanitrostilbene and the hexanitrobibenzyl by adding aqueous alkali, while an increase in the amount of the trinitrotoluene concentration relative to that of the chloride favors the bibenzyl-forming reaction compared with the stilbene-forming reaction.

Since the formation of carbanion 3 (eq 7) is the slowest step in the overall reaction, the overall rate should be first order in benzyl cyanide and a base, which is observed in the case of this reaction.

Experimental Section

Materials. Substituted benzyl cyanides were prepared by the treatment of benzyl chloride with sodium cyanide in ethanol.[19] Benzyl cyanides were purified by distillation. Substituents of benzyl cyanides and boiling points were as follows: unsubstituted, bp 95–96° (9 mm); *p*-Cl, bp 112–115° (5 mm); *p*-Me, bp 80–82° (4 mm); *p*-MeO, bp 116–118° (4 mm). *tert*-Butyl hypochlorite was prepared by the treatment of *tert*-butyl alcohol with molecular chlorine in aqueous sodium hydroxide.[20] α-Chlorobenzyl cyanide was prepared by the reaction of thionyl chloride with benzaldehyde cyanohydrin, bp 97–99° (5 mm).[21] 2,3-Diphenylsuccinonitrile was prepared by the treatment of benzaldehyde with a mixture of benzyl cyanide and sodium cyanide in aqueous ethanol,[22] and purified by recrystallization from methanol–water, mp 236–238° (mesomer). Solutions of bases were prepared by addition of dry sodium *tert*-butoxide or aqueous sodium hydroxide to pure dioxane, dried by metallic Na. The concentration of base was determined by acidmetry with HCl.

Products. The reaction of benzyl cyanides with iodine in ether–methanol containing sodium methoxide at 25° gave α,α'-dicyanostilbenes, which were recrystallized from methanol. Substituents of α,α'-dicyanostilbenes, yields, and their physical properties were as follows: unsubstituted, 50–85%, mp 162–163°, $\lambda_{\max}$ (MeOH) 324 nm (ϵ 19,000); *p*-Cl, 65%, mp 269–272°, $\lambda_{\max}$ (MeOH) 340 nm (ϵ 12,800); *p*-Me, 90%, mp 200–202°, $\lambda_{\max}$ (MeOH) 345 nm (ϵ 19,000); *p*-MeO, 85%, mp 204–205°, $\lambda_{\max}$ (MeOH) 375 nm (ϵ 19,500).

When the reactions of benzyl cyanides were carried out with *tert*-butyl hypochlorite instead of iodine in solvents such as ether, dioxane, *tert*-butyl alcohol, and methanol containing a base such as sodium methoxide or *tert*-butoxide at 25°, the same products were obtained in similar yields as above (50–95%). However, when the reactions of benzyl cyanide were carried out with *tert*-butyl hypochlorite in the presence of excess sodium *tert*-butoxide at 50° in *tert*-butyl alcohol (addition of 1.0 g of *tert*-butyl hypochlorite into a mixture of 1.0 g of benzyl cyanide, 5.0 g of sodium *tert*-butoxide, and 20 ml of *tert*-butyl alcohol), a small amount of α,α'-dicyanostilbene (1.0 g, 10%) was obtained together with 2,3-diphenylsuccinonitrile (1.0 g, 10%) and other dark brown byproducts. 2,3-Diphenylsuccinonitrile is hardly soluble in ether, and separated from other products. The obtained material was washed with methanol and dried, mp 236–238°, which was not decreased on admixture with the authentic sample. Infrared spectra of the two samples were identical.

When 20 ml of *tert*-butyl alcohol containing 1.0 g of sodium *tert*-butoxide was poured into a mixture of 1.0 g of benzyl cyanide, 4.0 g of *tert*-butyl hypochlorite, and 20 ml of *tert*-butyl alcohol, α,α'-dicyanostilbene (0.25 g, 50%) was obtained together with α,α-dichlorobenzyl cyanide (1.0 g), which was isolated by column chromatography: ir 2235 (CN), 725, 688 (monosubstituted phenyl), 790, 648 cm^{-1} (C-Cl); nmr (CCl$_4$) δ 8.00–7.30 (m, phenyl).

When gaseous chlorine was bubbled into a mixture of 1.2 g of benzyl cyanide and 20 ml of 1 *M* sodium methoxide in methanol in an ice bath below 50°, α,α-dichlorophenylacetamide (0.8 g) was obtained: mp 110° (lit.[23] mp 111–112°); ir 3230, 1740, 1715, 1620 (CONH$_2$), 730, 695 (monosubstituted phenyl), 790, 645 cm^{-1} (C-Cl); nmr (DMSO-d_6) δ 8.00–7.32 (m, 5 H, phenyl), 5.60 (broad singlet, 2 H, NH$_2$).

Anal. Calcd for $C_8H_7NOCl_2$: C, 47.1; H, 3.50; N, 6.9. Found: C, 49.3; H, 3.58; N, 7.5.

Kinetics. The kinetic experiments for the reaction of benzyl cyanides, 2,3-diphenylsuccinontrile, and α-chlorobenzyl cyanide were carried out in dioxane. Dioxane was selected as a solvent for its stability against hypohalites. Primary alcohols and acetone were unstable against hypohalites. Typical experiments for benzyl cyanides were as follows. The reaction was started by addition of a solution of base to a mixture of benzyl cyanides and molecular iodine or hypochlorite in a solvent placed in a 10 × 10 mm quartz cell which was thermostated with flowing water at constant temperature.

The plots of concentrations of dicyanostilbenes against time were linear under these conditions (*ca.* 1–10% conversion). The rate constants were calculated from the slopes of the straight lines which were obtained by plotting the initial rate against initial concentration of reactants.

The rate could not be measured accurately by means of uv, glc, or titrimetric analysis of pipetted-out aliquot because of the following reasons. (1) The reaction is too fast to measure. (2) Bases are only slightly soluble in dioxane, hence following the reaction by acidimetry is difficult. (3) The concentration of hypohalites changes gradually by spontaneous decomposition during the measurement. Therefore, we measured the rate by means of uv alone which enables the rapid measurement in dilute concentrations.

The reaction can only be followed by observing the uv spectrum of the product at λ_{max} stated above, where the absorbtion of substrate is very small (for example, in the case of benzyl cyanide, the values of ϵ at 324 nm follow: PhCH$_2$CN, 0; I$_2$, 520), and its change is negligible, and there is no disturbance of spectrum by the presence of by-products. The spectrum of the substrate cannot be used because of the overlapping of the absorption peaks. The solution must be very dilute for uv spectrophotometry, so that the measurement requires a long time and then the spontaneous decomposition of hypohalites may occur during the measurement; hence the rate constant had to be estimated by measuring rate under conditions of excess amount of reagents. Further, an increase of conversion by the longer reaction time resulted in so high a concentration of product that it was unsuitable for uv spectrophotometry. In order to confirm the rate law, the concentration of product was followed to higher conversion (*ca.* 38%) with highly diluted reaction system. A second-order plot of ln $\{[PhCH_2CN]_0{}^2([NaOH]_0 - 2[I_2]_0 - 4[PhC(CN){=}C(CN)Ph])/([NaOH]_0 - 2[I_2]_0)([PhCH_2CN]_0 - 2(PhC(CN){=}C(CN)Ph])^2\}$ against time was linear as shown in Figure 1 and the rate constant k estimated from the slope of the line ($k = 12.8 \times 10^{-4}\ M^{-1}\ \text{sec}^{-1}$) was consistent with that from the initial rate ($k = 16.2 \times 10^{-4}\ M^{-1}\ \text{sec}^{-1}$).

The rates of the reaction of α-chlorobenzyl cyanide and 2,3-diphenylsuccinonitrile were measured by the same way, and their constants were calculated similarly.

Registry No. 2,3-Diphenylsuccinonitrile, 5424-86-2; α-chlorobenzyl cyanide, 22259-83-2; α,α'-dicyanostilbene, 17656-09-6; p,p'-dichloro-α,α'-dicyanostilbene, 4591-17-7; p,p'-dimethyl-α,α'-dicyanostilbene, 4941-71-3; p,p'-dimethoxy-α,α'-dicyanostilbene, 43187-50-4; α,α-dichlorophenylacetamide, 7598-13-2.

References and Notes

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(14) An alternative mechanism involving a radical anion is not appropriate in view of the following facts. (1) The reaction is not accelerated by irradiation of light and occurs even in the dark. (2) The formation of radical anion seems to need the presence of nitro groups, but our substrates have no nitro group [R. C. Keber, G. W. Urry, and N. Kornblum, *J. Amer. Chem. Soc.*, **87**, 4520 (1965); H. B. Hass and M. L. Bendey, *ibid.*, **71**, 3482 (1949)]. (3) We confirmed that α-chlorobenzyl cyanide reacts in dioxane–methanol with sodium methoxide to form dicyanostilbene even in the presence of a free-radical inhibitor such as dinitrobenzene. Furthermore, the following mechanism involving a radical anion as in the literature

$$\underset{\text{I}}{\text{ArCHClCN}} + \underset{\text{II}}{\text{OR}^-} \rightleftharpoons \underset{\text{III}}{\text{Ar}\bar{\text{C}}\text{ClCN}} + \text{ROH}$$

$$\text{I} + \text{III} \rightleftharpoons \underset{\text{IV}}{\text{Ar}\dot{\text{C}}\text{ClCN}} + \underset{\text{V}}{(\text{ArCHClCN})\cdot^-}$$

$$\text{V} \rightleftharpoons \underset{\text{VI}}{\text{Ar}\dot{\text{C}}\text{HCN}} + \text{Cl}^-$$

$$\text{IV} + \text{VI} \longrightarrow \underset{\text{VII}}{\text{ArCH(CN)CCl(CN)Ar}}$$

and/or

$$\text{III} + \text{VI} \rightleftharpoons \underset{\text{VIII}}{[\text{ArCH(CN)CCl(CN)Ar}]\cdot^-}$$

$$\text{VIII} + \text{I} \rightleftharpoons \text{VII} + \text{V}$$

$$\text{VII} + \text{II} \longrightarrow \underset{\text{IX}}{\text{ArC(CN)}{=}\text{C(CN)Ar}}$$

[ref 4 and references in (2); G. A. Russell and C. Daven, *J. Amer. Chem. Soc.*, **90**, 347 (1968); H. Feuer, *J. Org. Chem.*, **38**, 417 (1973)] is not consistent with our observation; *i.e.*, the mechanism leads to the rate equation $v = k[\text{I}][\text{II}]$, $v = k[\text{I}]^2[\text{II}]$, or more complex ones which are not consistent with our kinetic data; also no formation of bibenzyl, the coupling product of VI, ruled out the equation involving VI.

(15) There may be other equilibria (ref 16b) such as

$$\text{I}_2 + \text{I}^- \rightleftharpoons \text{I}_3$$

$$\text{I}_3{}^- + 2\text{OH}^- \rightleftharpoons \text{IO}^- + 2\text{I}^-$$

$$\text{I}_2\text{OH}^- + \text{OH}^- \rightleftharpoons \text{IO}^- + \text{I}^- + \text{H}_2\text{O}$$

$$\text{I}_2\text{O}^{2-} \rightleftharpoons \text{IO}^- + \text{I}^-$$

However, since these equilibria are complex and their accurate constants are unknown, we calculated the remaining base concentration and rate constant by assuming that the equilibrium constant of eq 6 is much larger than unity and other equilibria shift to the right in analogy with the same reaction in aqueous solution (ref 16b).

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