

REACTIONS OF CYANIDE ION WITH METHYL 3,5-DINITROBENZOATE AND 3,5-DINITROBENZONITRILE

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Kinetics have been studied of the reaction of cyanide ion with 1-carbomethoxy- and -1-cyano-3,5-dinitrobenzene in methanol-dimethyl sulphoxide medium. Addition of cyanide ion to the 4-position of the both substrates is about three times as fast as that to 2-position. The symmetrical complex formed is less stable thermodynamically, and it mostly undergoes isomerization into the unsymmetrical one. The both products are decomposed in the reaction medium, the decomposition being catalyzed by cyanide ion. The influence of the 1-substituents on the rate constants of formation and decomposition of the both isomeric complexes is discussed.

1-Substituted 3,5-dinitrobenzenes react with carbanions to give two isomeric Meisenheimer complexes (Scheme 1). As a rule, the complex *II* is formed faster, but it is less stable than the complex *III*, and, therefore, it undergoes isomerization into *III* during the reaction^{1,2}. The kinetics of formation and decomposition of complexes of the type *II* and *III* were studied in more detail in the case of the reaction of 3,5-dinitrobenzoic acid piperidide with acetone anion² and reaction of 3,5-dinitrobenzoic acid piperidide, methyl ester and nitrile with cyclohexanone anion³. In the both cases the reactions were carried out in the mixtures ketone-methanol in the presence of methoxide ion.

The present paper deals with the formation of Meisenheimer complexes from 1-cyano- (*Ia*) and 1-carbomethoxy-3,5-dinitrobenzene (*Ib*) and cyanide ion. Its purpose was to determine the structure of the complexes formed, the rate constants of the reactions in Scheme 1 and their comparison with reactions of the same substrates with other nucleophiles.

EXPERIMENTAL

Reagents

3,5-Dinitrobenzonitrile⁴ (*Ia*), m.p. 128–129°C (1-butanol; ref.⁴ m.p. 127°C) and methyl 3,5-dinitrobenzoate¹ (*Ib*), m.p. 106–108°C (ref.¹ m.p. 112°C). Dimethyl sulphoxide was dried with calcium oxide and distilled *in vacuo*. The other chemicals used were commercial reagents of *p.a.* purity grade.

NMR Spectra

2M Solution of nitrile *Ia* (0.2 ml) in dimethyl sulphoxide was mixed with 1 ml 0.35M sodium cyanide solution in the same solvent. The both solutions were cooled to about 10°C before mixing. In analogous way solution of the complex of ester *Ib* with cyanide ion was prepared. Immediately after the preparation of the solutions the NMR spectra of the complexes were measured with the use of a Tesla BS 487 B (80 MHz) apparatus at the room temperature (internal standard: dimethyl sulphoxide, τ 7.50). First of all the whole spectrum was recorded at a higher speed, and then the measurement was repeated at a lower speed with freshly prepared solutions of the complexes, the records being limited to those regions where the proton absorption occurred. The procedure described had to be used due to low stability of the complexes.

Kinetic Measurements

Preliminary kinetic measurements were carried out with a Unicam SP 800 spectrophotometer at 25°C by recording the reaction solutions spectra within 350–700 nm at regular time intervals. Dimethyl sulphoxide or its mixture with methanol were used as reaction media. The conditions of pseudomonomolecular reaction course were used, *i.e.* either excess of cyanide ion or, more often, that of the substrate. The proper kinetic measurements of the isomerization and reverse reactions were carried out with a Zeiss VSU 2P spectrophotometer at 25°C in mixtures dimethyl sulphoxide–methanol, the methanol content being 20, 28 resp. 48% by vol. Solution of 0.1M nitrile *Ia* resp. 0.012M ester *Ib* in the mentioned solvent mixture was tempered at 25°C. In the isomerization reaction measurements, 20 μ l $4 \cdot 10^{-3}$ M methanolic sodium cyanide was injected into 2 ml of the solution mentioned in a 1 cm cell. At regular time intervals the absorbance decreases were measured at 530 nm (λ_{\max} is 528 and 540 nm for the complexes *IIIa* and *IIIb*, respectively). In the reverse reaction study of the complexes *IIa, b*, again 20 μ l $4 \cdot 10^{-3}$ M-NaCN was injected into 2 ml solution of the nitrile *Ia* resp. ester *Ib* in dimethyl sulphoxide–methanol mixture, the solution was shaken and, after 5 to 10 seconds, 20 μ l 0.2 to 5M methanolic chloroacetic was injected thereto. The absorbance decreases of the complexes *IIa, b* were measured at λ 620 nm. When following the reverse reaction of the complexes *IIIa, b* the procedure was the same, only the time interval between the two injections (cyanide, chloroacetic acid) being longer (about 5 half-lives of the isomerization reaction). In this case the absorbance decrease was measured at λ 530 nm. The rate constants were calculated from the time dependence of $\log (E_{\infty} - E_t)$ resp. $\log (E_t - E_{\infty})$.

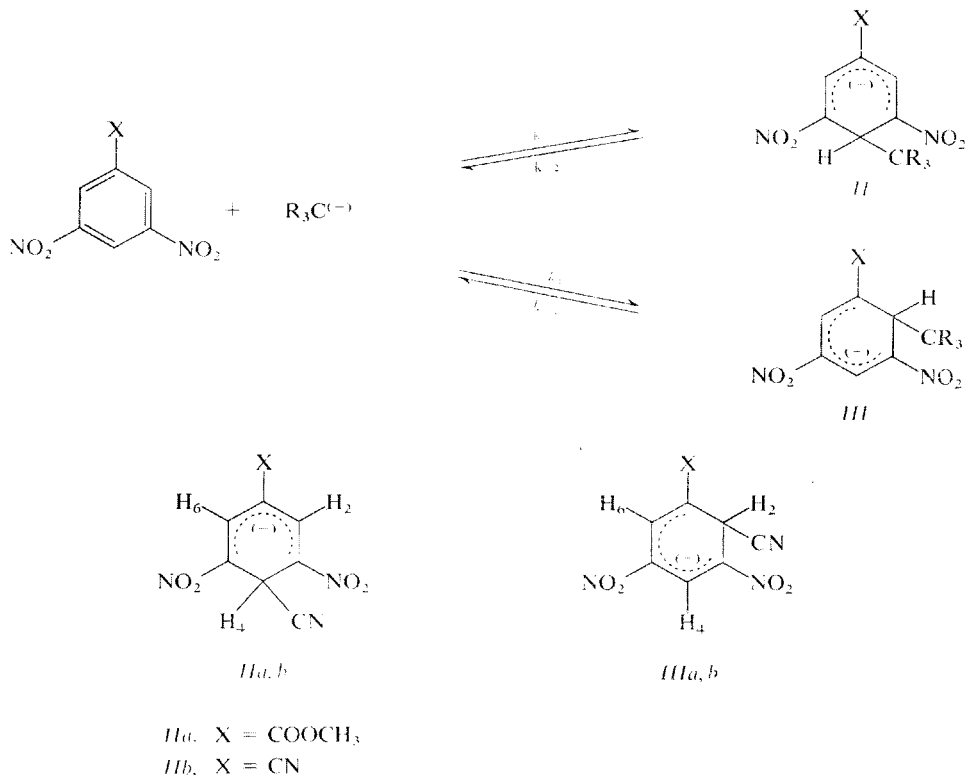
The rates of formation of the Meisenheimer complexes were measured with a Durrum Stopped Flow Spectrophotometer. One syringe was filled with 10^{-4} M solution of ester *Ib* in a mixture dimethyl sulphoxide–methanol (72 : 28 by vol.). The other one contained 0.1 to 0.019M-NaCN in the same solvent mixture. The reaction was started by mixing the same volumes of the both solutions. In the second experiment series the first syringe contained 10^{-4} M solutions of ester *Ib* or nitrile *Ia* in the same solvent mixture, and the second one contained a mixture of sodium and hydrogen cyanides (6 : 1), the concentration of the former being 0.01 to 0.06M. The absorbance change was followed at 620 nm and, in some cases, 450 nm. The reaction half-life was determined from the absorbance–time dependence at 620 nm recorded on the oscilloscope of the spectrophotometer. The rate constant was calculated from the relation $k = 0.693/\tau_{1/2}$.

RESULTS AND DISCUSSION

Cyanide ion, as the other carbanions too, reacts with 1-X-3,5-dinitrobenzenes to give two isomeric Meisenheimer complexes type *II* and *III*. Their structure and

approximative population in the reaction mixture could be determined from NMR spectra.

In the region of absorption of protons at sp^2 carbon atoms of the complexes from *Ia* three absorptions were observed. Two of them of equal intensities were broadened by spin-spin coupling (1.60τ and 2.55τ) and belonged to H^4 and H^6 proton of the complex *IIIa*. Approximate value of the coupling constant $J_{4,6}$ is 2 Hz. The third relatively sharp and more intensive signal (2.21τ) is due to the protons H^2 and H^6 of the complex *IIa*. In the region of the absorption of the protons at the sp^3 carbons two absorptions were found: 4.36 and 4.88τ . On the basis of intensities and chemical shifts the two absorptions at 4.36τ and 4.38τ were ascribed to the proton H^4 of the complex *IIa* and proton H^2 of the complex *IIIa*, respectively. From intensities of these signals it was possible to estimate the *IIa* to *IIIa* ratio in the reaction mixture to be 3 : 1. However, within few minutes this ratio increased considerably, because the complex *IIIa* irreversibly decomposed far faster than *IIa*. Character of spectrum of the complexes formed from *Ib* is quite analogous. The complexes *IIb* and *IIIb* are more stable than the above ones, and the spectrum obtained was much better. The following



SCHEME 1

values of chemical shifts were found for the individual protons of complexes *I Ib* resp. *III b*: 1.92τ ($H^2 + H^6$), 4.34τ (H^4) resp. 4.74τ (H^2); 1.67τ (H^4); 2.11τ (H^6). The estimated ratio of population of the both isomers [*I Ib*]/[*III b*] is (2.5 to 3) : 1.

Symmetrical complexes *I Ia* and *I Ib* ($X = \text{CN}, \text{CO}_2\text{CH}_3$) absorbing at higher wavelengths (λ_{max} 610 nm) are less stable thermodynamically and are transformed into more stable unsymmetrical complexes *III a, b* (λ_{max} 530 nm) during the reaction. In pure methanol the equilibrium constants of formation of the both complexes with cyanide ion are so small that the reaction cannot be followed in this medium. Therefore, the mixtures dimethyl sulphoxide–methanol of various ratios were used as the reaction medium. Increasing dimethyl sulphoxide concentration brings about a great increase in the rate constant of formation (k_2, k_3) and a substantially smaller decrease in the reverse reaction rate constants (k_{-2}, k_{-3}).

Preliminary experiments were carried out under usual conditions, *i.e.* with a great excess of nucleophile (cyanide ion) as compared with the substrate. Under these conditions rapid decomposition reactions of the Meisenheimer complexes took place, especially so with the complex *III a* where the decomposition half-lives were shorter than 1 minute. The decomposition rates increased with increasing sodium cyanide concentration. Similar decomposition reactions were observed in measurements of equilibrium constants of formation of complexes of 1,3,5-trinitrobenzene with cyanide ion⁵. With high excess of 1-X-3,5-dinitrobenzene the decomposition rates were low, and they further decreased with increasing substrate concentration. Therefore, we used this way of measurement in the study of the isomerization reaction and its retrogression. If chloroacetic acid is added into the reaction mixture after conversion of most cyanide ion into the both isomeric complexes, practically only the reverse reactions of the complexes take place, the absorbances in the long-wave region being decreased to zero. If, instead of chloroacetic acid, weaker acetic acid is added into the reaction mixture, the absorbances do not decrease down to zero value, but an equilibrium mixture is formed the composition of which depends on concentration of acetic acid, dimethylsulphoxide, substrate, and on its structure. Establishing of these equilibria indicates that the reactions studied are reversible (Scheme 1) under the conditions mentioned. At higher chloroacetic acid concentrations ($>0.02\text{M}$) the reverse reaction is accelerated especially with the complex *III a*. The values of the reverse reaction rate constants given in Table I were determined at the concentration of maximum 0.01M chloroacetic acid.

The isomerization rate constants were measured with a large excess of the dinitro compound, so that the rate of formation of the products was at least by 2 orders of magnitude greater than the isomerization rate, and the cyanide concentration was negligible compared with concentration of the Meisenheimer complexes during the measurements. In this case the isomerization rate constants can be defined by Eq. (1),

$$k_{\text{iso}} = \vec{k} + \bar{k} = (k_{-2}k_3)/(k_2 + k_3) + (k_{-3}k_2)/(k_2 + k_3), \quad (1)$$

where \vec{k} and \overleftarrow{k} are the rate constants of the transformations $II \rightleftharpoons III$. Eq. (1) can be modified to give Eq. (2)

$$k_2/k_3 = (k_{-2} - k_{iso})/(k_{iso} - k_{-3}). \quad (2)$$

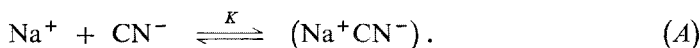
By introducing the measured rate constants k_{-2} , k_{-3} and k_{iso} into Eq. (2) the ratios k_2/k_3 of rates of formations of the both complexes were obtained (Table I).

The rate constants k_2 and k_3 were measured with excess cyanide ion, because otherwise (with about $4 \cdot 10^{-5} M$ cyanide concentration) cyanide ion is protonated by methanol or by the dissolved carbon dioxide resp. other acidic impurities present in traces. This fact decreases the effective cyanide ion concentration and thus also the experimental rate constant. The rate of formation of the Meisenheimer complexes is far greater (at least by 2 orders of magnitude) than that of the isomerisation and decomposition reactions even at high cyanide ion concentrations.

Besides the proper reaction also reaction of the substrate with methoxide ion (formed by reaction of cyanide with methanol) can take place to a lesser extent. In order to find the extent of this simultaneous formation of the Meisenheimer complexes with methoxide ion, we measured, besides the absorbance changes at 620 nm, also those at 450 nm where these complexes absorb much more strongly than the complexes with cyanide ion.

In reaction with ester of 3,5-dinitrobenzoic acid an exponential absorbance increase was observed at the both wavelengths. The experimental rate constant is given by Eq. (3).

$$k_{exp} = (k_2 + k_3) \cdot [CN^-], \quad (3)$$



The dependence of the rate constant k_{exp} on the sodium cyanide concentration was not linear, its slope being decreased with increasing concentration. This fact would suggest that, in the medium given, cyanide and sodium ions associate to ionic pairs (Eq. (4)). When plotting the rate constants k_{exp} against the square root of sodium cyanide concentration it was found that the slope of the dependence increased with increasing cyanide concentration. It means that comparable concentrations of cyanide ions and ionic pairs are present in the reaction medium. A linear dependence of k_{exp} vs $[CN^-]$ was obtained when the value 400 l mol^{-1} was used for the equilibrium constant K in the calculation of free cyanide ion concentration (Table II).

In reaction of cyanide ion with 3,5-dinitrobenzotrile the time dependence of the absorbance at 620 nm was not exponential. After a certain time the absorbance increase was considerably slowed down. At 450 nm a rapid increase was observed followed by a slower absorbance decrease. It means that, in this case, practically irreversible reactions with cyanide ion take place to an extent comparable to that of

the reversible reactions with methoxide ion, and that the reaction with methoxide ion is somewhat faster. At the same time the more rapidly formed but less stable complex with methoxide ion is transformed gradually into the complex with cyanide ion. This situation is rather complex from the kinetic point of view, and, therefore, we used the following procedure for determination of the rate constants k_2 and k_3 .

TABLE I

Rate Constants of Formation (k_2, k_3 ; $l \text{ mol}^{-1} \text{ s}^{-1}$), Reverse Reaction (k_{-2}, k_{-3} ; s^{-1}) and Isomerization (k_{iso} ; s^{-1}) of Meisenheimer Complexes of 3,5-Dinitrobenzotrile and Methyl 3,5-Dinitrobenzoate with Cyanide Ion in Dimethyl Sulphoxide–Methanol Mixtures at 25°C

Medium ^a	$k_{\text{iso}} \cdot 10^4$	$k_{-2} \cdot 10^4$	$k_{-3} \cdot 10^4$	k_2/k_3	K_3/K_2
<i>Ia</i>					
B	15.7 ± 1.0	42.8 ± 1.7	5.4 ± 0.2^b	2.75	2.78
C	20.7 ± 2.0	61.0 ± 2.0	7.0 ± 0.3	3.04	2.68
<i>Ib</i>					
A	17.2 ± 1.3	61.0 ± 3.0	3.35 ± 0.17	3.16	5.77
B	25.3 ± 2.6	72.0 ± 6.5	4.5 ± 0.2^c	2.48	6.90

^a A 20% by vol. methanol in dimethyl sulphoxide, B 28% by vol. methanol, C 40% by vol. methanol. ^b $k_2 = 721 \text{ l mol}^{-1} \text{ s}^{-1}$, $k_3 = 259 \text{ l mol}^{-1} \text{ s}^{-1}$. ^c $k_2 = 142.5 \text{ l mol}^{-1} \text{ s}^{-1}$, $k_3 = 57.5 \text{ l mol}^{-1} \text{ s}^{-1}$.

TABLE II

Dependence of k_{exp} (s^{-1}) on Analytical Concentration of Sodium Cyanide (mol l^{-1}) and Effective Concentration of CN^- Ion in Mixture Dimethyl Sulphoxide–Methanol (72 : 28 by vol.)

NaCN · 10 ²	$[\text{CN}^-] \cdot 10^3$	k_{exp}^a	$k_{\text{exp}}[\text{CN}^-]^{-1}$
4.65	9.60	1.92	200
2.79	7.20	1.44	200
1.86	5.70	1.15	198
0.93	3.75	0.77	204
5.04	10.00	1.98	198
3.60	8.30	1.61	194
2.16	6.20	1.12	182

^a The rate constant of formation of the both isomeric complexes of methyl 3,5-dinitrobenzoate defined by Eq. (3).

Instead of pure sodium cyanide solution its mixture with hydrogen cyanide (6 : 1) was used. Under these conditions the formation of methoxide ion is suppressed to such an extent that its reaction with the nitrile is not significant. The absorbance increase at the both wavelengths (620 and 450 nm) was in this case exponential. The same buffered solutions (sodium and hydrogen cyanide) were used simultaneously for measurements of the reaction with ester, and from the found ratio 4.9 ± 0.2 of the rate constants obtained under the same conditions the sum $k_2 + k_3$ was calculated for the reaction of cyanide ion with nitrile.

The rate constants ratio k_2/k_3 is about 2.8 for the both substrates studied, which is somewhat more than that for the reaction of nitrile with hydroxyl ion⁶ and substantially more than that for the reaction with acetone² and cyclohexanone³ anions where the ratio was even less than unity. The ratio of the equilibrium constants of formation of the both complexes (Table I) is substantially smaller than that for most reactions of these substrates with other nucleophiles^{3,6}. The rate constant k_2 for the reaction with the nitrile is about 5 times greater than that for the reaction with the ester. In the reaction with cyclohexanone³ this ratio was 15, in spite of that cyclohexanone anion is a far stronger nucleophile, and that it should be less selective. The influence of substituents on k_{-2} is substantially smaller as it is the case with the reactions of other nucleophiles.

Influence of substituents on the rate constants k_3 is similar to that on k_2 , in spite of that here the addition in *ortho*-position is taking place. On the contrary, in the reverse reactions (the rate constants k_{-3}) specific influence of *ortho*-group is obviously operating, because k_{-3} of the nitrile is even greater than that of the ester (Table I).

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