Addition of Cyanide Ions to Aromatic Aldehydes: a Competition Method for the Determination of Equilibrium Constants of Nucleophilic Addition Reactions

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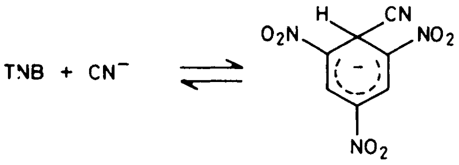
The equilibrium concentration of the cyanide Meisenheimer adduct of 1,3,5-trinitrobenzene, formed from potassium cyanide–18-crown-6 and trinitrobenzene, in DMSO solution, is reduced in the presence of an aromatic aldehyde, with an accompanying decrease in the absorbance of the solution due to the intensely coloured Meisenheimer adduct. Equilibrium constants have accordingly been determined for the formation of the cyanide Meisenheimer adduct of trinitrobenzene and for the formation of members of a series of substituted benzaldehyde cyanohydrin anions in dimethyl sulphoxide solution.

Equilibrium constants for the addition of nucleophiles to carbonyl compounds can be determined either directly, by spectroscopic observation of the concentration of one or more of the chemical species involved in the equilibrium, or by measurement of rate constants of the reactions in the forward and reverse directions.[1] The present paper describes an indirect method for determining the equilibrium constant, by monitoring an 'indicator' equilibrium, and the results obtained by this method for the addition of cyanide ions in dimethyl sulphoxide (DMSO) solution to aromatic aldehydes. Cyanide ions add reversibly[2] to 1,3,5-trinitrobenzene (TNB) with formation of a coloured Meisenheimer adduct (I).[3] Spectrophotometric determination of the concentration of the adduct (I) allows evaluation of the equilibrium constant of reaction (1).



(I) (1)

$$\text{ArCHO} + \text{CN}^- \rightleftharpoons \text{ArCH(CN)O}^- \quad \text{(II)} \quad (2)$$

When the equilibrium (1) is established in the presence of an aldehyde, the reversible reaction (2) provides an alternative destination for the reactive cyanide. Concentrations are chosen so that the equilibrium concentration of free cyanide ions is negligible compared with that of the Meisenheimer adduct anion (I) or the cyanohydrin anion (II). The concentration of (I) then provides a probe for the position of the equilibrium (3). The

$$\text{ArCHO} + \text{(I)} \rightleftharpoons \text{TNB} + \text{ArCH(CN)O} \qquad (3)$$

equilibrium constants of the three reactions are related according to equation (4). In the absence of added aldehyde, the

$$K_3 = K_2/K_1 = \frac{[\text{TNB}]}{[\text{ArCHO}]}\cdot\frac{[\text{(II)}]}{[\text{(I)}]} \qquad (4)$$

observed concentration of (I) is equal to the stoicheiometric concentration of added cyanide ion $[\text{CN}^-]_{\text{st}}$, provided $[\text{(I)}] \gg [\text{CN}^-] \ll [\text{TNB}]$ (the subscript st indicates a stoicheiometric concentration). When aldehyde is present, the concentration of (I) is reduced by the equilibrium concentration of (II) in the system. Accordingly, if $A°$ and A represent the absorbance [due to (I)] in the absence and presence of added aldehyde, respectively, equation (5) applies.

$$\frac{A° - A}{A} = \frac{[\text{(II)}]}{[\text{(I)}]} \qquad (5)$$

Since $[\text{TNB}]_{\text{st}} \gg [\text{CN}^-]_{\text{st}} \ll [\text{ArCHO}]_{\text{st}}$, we may equate the stoicheiometric and equilibrium concentrations for the two species present in relatively high concentrations, so that equations (4) and (5) give (6).

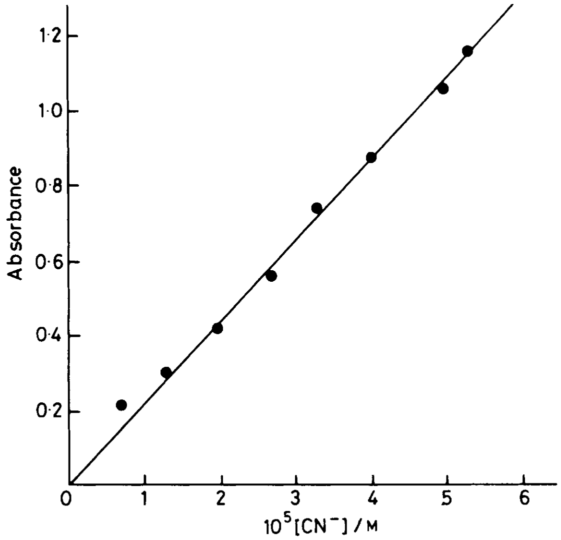


Figure 1. Illustration of quantitative conversion of cyanide ion into Meisenheimer adduct (I) at high concentration of TNB (2×10^{-3}M)

$$K_3 = \frac{[\text{TNB}]_{\text{st}}}{[\text{ArCHO}]_{\text{st}}}\cdot\frac{(A° - A)}{A} \qquad (6)$$

The cyanohydrin anions (II) are moderately strong bases, with (aqueous) pK_a values in the range 10.2—10.9.[6] In dry DMSO solutions their rapid protonation by solvent is not expected, nor does their addition to TNB appear to occur at a rate comparable with that of the reactions of interest.

The present paper is concerned with the application of equation (6) to the reaction between the members of a series of substituted benzaldehydes and potassium cyanide (with equimolar addition of 18-crown-6) in DMSO solution at 25 °C.

The procedure utilised is a thermodynamic counterpart of the kinetic competition method applicable when the competing reactions are, for practical purposes, irreversible.[7]

Experimental

The purification of DMSO, TNB, and aldehydes has previously been described. 18-Crown-6 was purified by complexation with acetonitrile.[8] A stock solution in DMSO containing potassium cyanide and 18-crown-6 in equal concentration (0.01M) was used. Appropriate amounts of the stock solution were added from a syringe to a well stirred solution of TNB at 25 °C. The absorbance of the solution was monitored in cells of 1 cm pathlength at 570 mm on a Pye-Unicam SP8-100 spectrophotometer. Its value immediately rose after mixing, too rapidly for rate measurements on that instrument. The absorption spectrum of the product solution was closely similar to that previously reported for (I) in different solvents.[2,9] The absorbance very slowly decreased with time, and the maximum value recorded almost immediately upon mixing was taken to be that corresponding to the equilibrium concentration of (I). All stock solutions were protected from light.

For solutions of cyanide–crown containing a relatively high concentration of TNB (2×10^{-3}M), without added aldehyde, the absorbance was proportional to the concentration of cyanide, indicating quantitative formation of (I) (Figure 1) with a molar absorption coefficient ε 2.18×10^4 l cm^{-1} mol^{-1}. At much lower concentrations of TNB the absorbance varies with the concentration of the reactants in a manner consistent with incomplete conversion into (I). A plot of these results (Table 1), in Figure 2, is based on equation (7) which is derived by re-

$$\frac{[\mathrm{CN}^-]_{\mathrm{st}}}{A} = \left[K_1\varepsilon([\mathrm{TNB}]_{\mathrm{st}} - \frac{A}{\varepsilon})\right]^{-1} + \varepsilon^{-1} \qquad (7)$$

$$K_1 = \frac{[(\mathrm{I})]}{([\mathrm{TNB}]_{\mathrm{st}} - [(\mathrm{I})])([\mathrm{CN}^-]_{\mathrm{st}} - [(\mathrm{I})])} \qquad (8)$$

arrangement of the equilibrium expression (8) for reaction (1) with the substitution $[(\mathrm{I})] = A/\varepsilon$. The straight line in Figure 2 is drawn through an intercept of $(2.18 \times 10^4)^{-1}$ mol cm l^{-1}; its slope corresponds to a value of 1.2×10^5M for the equilibrium constant K_1.

Table 1. Absorbance measurements at low stoicheiometric concentrations of cyanide ion * (5×10^{-5}M) and TNB

10^5 [TNB]/M	Absorbance at 570 nm
3.30	0.545
4.95	0.723
6.60	0.870
13.20	0.903
16.50	1.151
30.00	1.332

* Added as KCN–18-crown-6.

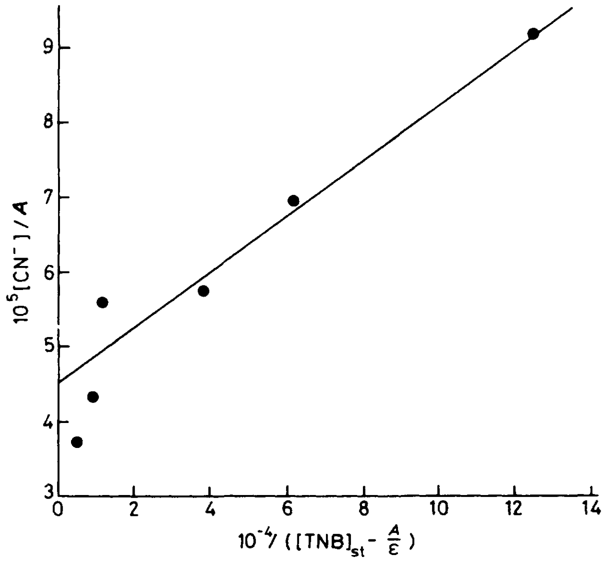


Figure 2. Test of equation (7) for evaluation of K_1 from absorbance measurements at low concentrations of TNB

Table 2. Absorbance measurements for solutions containing cyanide ion, TNB, and aromatic aldehydes (RC_6H_4CHO)

	$(A^\circ - A)/A$						
$[\mathrm{ArCHO}]_{\mathrm{st}}/[\mathrm{TNB}]_{\mathrm{st}}$	R = *p*-NO_2	R = *m*-NO_2	R = *p*-Cl	R = *m*-Cl	R = H	R = *p*-CH_3	R = *p*-OCH_3
1	0.140	0.072		0.070			
2	0.217	0.250	0.172	0.151	0.043		
2.5	0.374						
3		0.352		0.210			
4	0.523	0.613			0.234		
5	0.830	0.750	0.320	0.384			
6	0.985	0.911		0.415			
6.25					0.254		
7		1.000					
8	1.181		0.431	0.732			
10	1.905		0.685	0.850		0.135	0.158
12.5			0.724		0.451		
15				1.561			
16			0.929				
20			1.006			0.220	0.256
25					0.640	0.269	
30						0.319	0.357
37.5					1.061		
40						0.408	
50					1.501		0.675
65						0.653	0.810
100						0.978	1.215
150						1.254	1.518

Cyanide added as KCN–18-crown-6. $[\mathrm{TNB}]_{\mathrm{st}}$ 3.2×10^{-3} M.

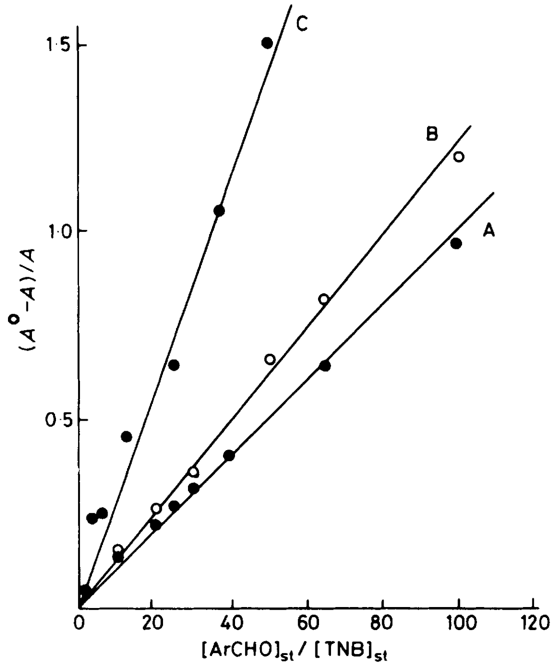


Figure 3. Specimen graphs for evaluation of K_3 from equation (6): A, 4-$CH_3OC_6H_4CHO$; B, 4-$CH_3C_6H_4CHO$; C, C_6H_5CHO

Table 3. Equilibrium constants for formation of cyanohydrin anions from aldehydes RC_6H_4CHO

R	10^3K_3[a] in DMSO	$10^{-2}K_2$[a] in DMSO	K_2 in H_2O[b]	σ	σ^+
p-NO_2	168	202	141	0.778	0.790
m-NO_2	132	158		0.710	0.674
m-Cl	80	96		0.373	0.399
p-Cl	62	74	7.2	0.227	0.114
H	32	38	5.5	0	0
p-CH_3	13	16	1.68	−0.170	−0.311
p-OCH_3	10	12	0.5	−0.268	−0.778
ρ		1.3			
ρ^+		0.9	1.5		

[a] This work. [b] Ching and Kallen.[6] Data for 25 °C and $I = 1$.

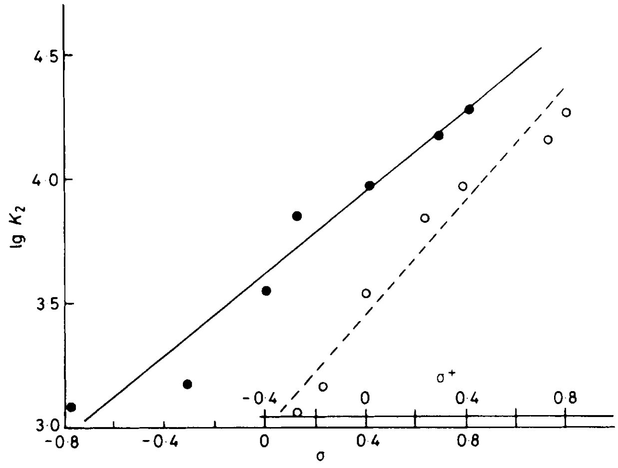


Figure 4. ρ–σ and ρ–σ^+ correlations for K_2 values

Results for measurements with aldehydes are given in Table 2, where A° and A are the observed absorbances in the absence and in the presence of added aldehyde. From the slopes of graphs (Figure 3) of $(A^\circ - A)/A$ against $[ArCHO]_{st}/[TNB]_{st}$ at low concentrations, values of K_3 were obtained according to equation (6). The equilibrium constants K_2 were calculated *via* equation (4) using the above value of K_1.

Discussion

The use of equations (6), (7), and (4) for the evaluation of the equilibrium constants for reactions (1)—(3), respectively, has been demonstrated in the Experimental section. The usefulness of the procedure depends on the high molar absorption coefficient of (I), which allows the measurements to be carried out on very dilute solutions.

Equilibria involving cyanide ions as a nucleophile have frequently been studied in the past. A variety of solvents have been used but the present study appears to be the first one using DMSO. To minimise possible effects of ion association between potassium and cyanide ions, we have followed the stratagem of carrying out the measurements in the presence of an equimolecular concentration of 18-crown-6.[10] It has previously been shown that the value of K_1 varies between 39 (in methanol) and 5×10^5 (in t-butyl alcohol) for a series of alcoholic solvents.[9] This trend can be associated both with the decreasing permittivity of the media and with their decreasing hydrogen bond donor strengths; both factors reduce the stability of the cyanide ion relative to (I) along the series. The solvation of anions is thought to be particularly weak in DMSO, despite its moderately high permittivity, and the high value of K_1 observed in this solvent (1.2×10^5 l mol^{-1}) is consistent with this view.

Similarly, values of K_2 are large compared with previously determined values relating to aqueous solution.[6] Results for both media are given in Table 3. Plots of lg K_2 against σ or σ^+ (Figure 4) lead to ρ values (given in Table 3) that are considerably lower for DMSO as solvent. Either plot has been used in the past for similar systems. In the present case the ρ–σ correlation appears to be more closely obeyed. The ρ-values are numerically smaller than for equilibria involving the addition of hydroxide[11] or methoxide anions[12] (in their respective solvents) to aromatic aldehydes. All these data further exemplify the rather special position of DMSO (and perhaps of similar non-hydroxylic media of relatively high permittivity) as a solvent for enhancing the reactivity (kinetic and thermodynamic) of anionic nucleophiles, an effect which has already extensively been exploited for the n.m.r. observation of Meisenheimer adducts.[13]

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