SOME REACTIONS OF SODIUM NITROPRUSSIDE AND RELATED COMPOUNDS.

A Thesis
presented for the degree of
MASTER OF SCIENCE
in the Faculty of Science of the
University of St. Andrews
by
VINUN CHAIPANICH, B. Sc.

St. Andrews October 1981

To my mother and my family whose financial support, inspiration and encouragement have made this possible.

DECLARATION

I hereby declare that this thesis is a record of the results of my own experiments, that it is my own work, and that it has not previously been presented in application for a higher degree.

The research was carried out in the chemistry Research Department of the University of St Andrews, Scotland under the supervision of Dr A R Butler and Dr C Glidewell.

CERTIFICATE

I hereby certify that Vinun Chaipanich has spent eight terms at research work under my supervision, has fulfilled the Conditions of the University Court 1974 No 2 (St Andrews) and he is qualified to submit the accompanying thesis in application for the degree of Master of Science.

Director of Research

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude to Dr A R Butler and Dr C Glidewell for their continued supervision, guidance and assistance throughout this research and for their advice on the writing of this thesis.

Thanks are due to the Chemistry Department as a whole for providing the means of carrying out this research in pleasant surroundings.

A special word is due also to Mrs Wilma Pogorzelec and to Miss Alison F Thom for careful typing of this thesis.

Last, but by no means least, to all my friends at St Andrews who have made my stay most enjoyable. Endless names can be quoted, but I would like to mention a few here. They are Mr Wan-Lung Wong, Dr Mashor Manshor, Dr Duncan MacKerron, Dr Richard Fardon, Miss Sharee Pritchard, Mr Javid Kalid, Mr Saeed Atto and Mr Joe McGinnis.

CONTENTS

Page

General introduction to reaction of sodium nitroprusside with carbanions

PART ONE

Studies of compounds related to sodium nitroprusside

Page

Preparation of related compounds

Potentiometric precipitation titrations for halogens

Page

PART TWO

Kinetic studies of the reaction between creatinine and sodium nitroprusside

PART THREE

Kinetic studies of the reaction between malononitrile and sodium nitroprusside

ABSTRACT

It is known that sodium nitroprusside $Na_2((CN)_5FeNO)2H_2O$ may be used as a drug to lower blood pressure in the human body. However, one disadvantage that has been reported is that patients receiving such treatment have increased toxic side effects, in some cases resulting in death.

The reported work is part of a general survey of the reactions of sodium nitroprusside. It covers the kinetics of the reactions of sodium nitroprusside with such carbanions as creatinine, as reported in chapter 2, and malononitrile as reported in chapter 3.

In chapter 1, I investigated various compounds related to sodium nitroprusside. The studies carried out were mainly descriptive and preparative ones, they all proved to be interesting, yet inconclusive.

The investigation of the kinetic of reaction between sodium nitroprusside and the two carbanions, namely creatinine and malononitrile, proved quite conclusive. The data for creatinine showed that it is a reaction of the first order in both creatinine carbanion and nitroprusside anions. The creatinine carbanions react with sodium nitroprusside to give a red coloration and it is this which is the rate-determining step.

However, the kinetic studies on malononitrile proved much more difficult to interpret in mechanistic terms than was the case for creatinine. The rate-determining step in this reaction is the slow removal of a proton from species $[(CN)_5FeNOCH(CN)_2]^{2-}$ by OH^- to form the red species $[(CN)_5FeNO(CN)_2]^{2}$. Furthermore, identities of the red intermediate and the organic product of the reaction were consistent

with the proposed mechanism.

The kinetic works on the carbanions were carried out using the stopped-flow spectrophotometer. In the creatinine study the S. F. S. was connected via a transcient recorder to a plótter. This traces out the observed curves for kinetic study. In the malononitrile study the S. F. S. was connected via a transcient recorder to a microcomputer which allowed immediate calculation of the rate constants. The computer programme has been written to assist in the calculation of rate constants for kinetic studies.

General Introduction to Reactions of Sodium Nitroprusside with Carbanions

Reaction of sodium nitroprusside with carbanions

Introduction

Sodium nitroprusside was first prepared in 1850 by Playfair[1]. It has been used for over a century as a reagent in the qualitative and quantitative analysis of organic and inorganic compounds.

Most of the preparative reactions described are between sodium ferro- or ferricyanide and nitric acid[2-6] or sodium nitrite[7-12]. Modern preparations[13] involve the passage of oxides of nitrogen through sodium ferro or ferricyanide solution[7], and the reaction between sodium nitrate and potassium ferrocyanide solution in the presence of sulphuric acid and ferric chloride[14]. Nitroprusside are formed when potassium ferrocyanide and potassium chlorate interact[15], and when potassium ferricyanide and calcium hypochloride are heated together in solution[16]. Sodium nitroprusside was originally prepared from gaseous thiocyanates, formed by heating a mixture of tar and sulphur. Electrolysis of potassium[17] ferrocyanide solution also yields nitroprussides[16].

Nomenclature

The NO moiety dominates the chemical and spectral properties of $[(NC)_5FeNO]^{2-}$ so much that most attention has been directed towards its electronic and structural elucidation.

i) X-ray study

The crystal structure of $Na_2[(NC)_5FeNO].2H_2O$ has only recently been determined[18]. The crystal is orthorhombic with space group P_{nnm}. The $[(NC)_5FeNO]^{2-}$ ion has approximate C_{4v} symmetry. The Fe-N distance is 1.63 ± 0.02 Å. This bond length is comparable with distances of between 1.57 and 1.71 Å observed for Roussin's black salt[19], $Cs[Fe_4S_3(NO)_7]$ and Roussin's red ethyl ether[20]. The rather short Fe-N bond distance suggests the presence of a large amount of triple bond character in this bond. The N-O distance is 1.13 ± 0.02 Å. The NO bond distances observed in NOX, where X is a halogen, are 1.14 ± 0.02 Å. The five C-N distances are 1.16 ± 0.02 Å and do not differ from the C-N bond distances in other cyanide complexes[21]. The Fe-C distances are equivalent for all of the cyanides at 1.90 ± 0.02 Å. This implies that no special structural characteristics exist for the axial or equatorial cyanides. The Fe-N-O angle is within experimental error 180°, which has important consequences in terms of the nature of the bond between the iron and the NO moiety. The N-Fe-C equatorial angle is 96°, slightly larger than the expected 90°.

ii) Infrared studies

In the past a substantial number of infrared studies have been carried out on nitrosyl complexes and $[(NC)_5FeNO]^{2-}$ in particular[23-29]. Table 1 contains a summary of NO and CN stretching frequency data in the literature. The NO stretching frequency can be compared with those of NO (1878 cm^{-1})[30] and NO^+ (2220 cm^{-1})[31]. Bonding of either of these species to a metal ion centre will lower the observed frequency. Upon examination of a wide variety of NO stretching frequencies in complexes Wilkinson et al[25, 32] have concluded that if the frequency lies in the range 1650 to 2000 cm^{-1} the NO moiety can formally be considered to be coordinated as NO^+. However, from a comparison of the CN stretching frequencies of $[Fe(CN)_6]^{3-}$, $[Fe(CN)_6]^{4-}$, and $[(NC)_5FeNO]^{2-}$ it is possible to conclude that the oxidation state of the iron in $[(NC)_5FeNO]^{2-}$ is plus three or four[24]. Tosi and Danon[27] conclude that the high CN stretching frequency of $[(NC)_5FeNO]^{2-}$ compared to other $[(NC)_6Fe^{II}X]$ complexes ($X = NH_3$, H_2O, NO_2^- and SO_3^{2-}) indicates less π-bonding in the Fe-C bond for $[(NC)_5FeNO]^{2-}$. The splitting of the CN stretch bond is consistent with the C_{4v} symmetry[22, 26] of $[(NC)_5FeNO]^{2-}$.

The far infrared region has been studied by several groups of workers. Tosi and Danon[27] find two groups of bands at 470, 497, 515 cm^{-1} and 420, 435, 450 cm^{-1}, which are attributed to Fe-C-N bending and Fe-C stretching[33]. Jezowska-Trzebiatowska and Ziolkowski[28] have determined the Fe-C-N bending (518 cm^{-1}) Fe-N-O bending (663 cm^{-1}), Fe-C stretching (422 cm^{-1}) and Fe-N stretching (496 cm^{-1}) frequencies[34]. No clear structural distinctions have been drawn from these observed frequencies.

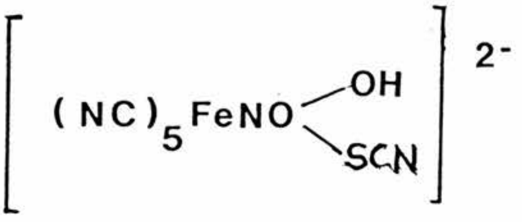
Table 1. Infrared data on $[(NC)_5FeNO]^{2-}$

Frequency, cm^{-1}		Ref.
NO stretch	CN stretch	
1925	2140	29
1938	2152	24
1925	-	25
1938	-	25
1944	2182, 2169, 2155	22
1939	2173,4, 2161.6, 2156.7, 2143.4	26
-	2170, 2160, 2148	27
1940	2144	28
1939	2173, 2159, 2142	29

Physical properties of sodium nitroprusside

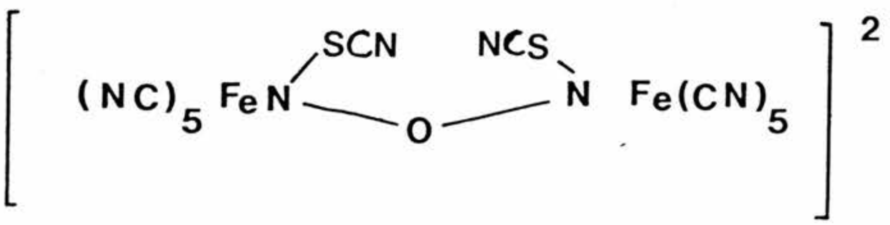
The compound crystallises rapidly from aqueous solutions as ruby-red prisms to specific gravity 1.71, which dissolve in water to give a dark red solution, but are not soluble in absolute ethanol. In the presence of light $[(NC)_5Fe\,NO]^{2-}$ undergoes numerous reaction, many of which are undefined. It is reported that irradiation of a neutral polution of $[(NC)_5FeNO]^{2-}$ results in a pH decrease, which increases to nearly the original value when the irradiation ceases[35]. The action of direct sunlight on $[(NC)_5FeNO]^{2-}$ ultimately yields Berlin blue or Prussian blue, [HCN and NO][36]. The immediate products of the photodecomposition of $[(NC)_5FeNO]^{2-}$ are apparently[40] NO and $[(NC)_5FeH_2O]^{2-}$. It is reported that $[(NC)_5FeNO]^{2-}$ is photoreduced in aqueous solution[21] to $[NC)_5FeNO]^{3-}$. No blue coloration $[(NC)_5NO\,H]^{2-}$, is observed when $[(NC)_5FeNO]^{2-}$ is irradiated with moderate intensity light in water over long periods of time. However, when $[(NC)_5FeNO]^{2-}$ is irradiated in the presence of thiocyanate[37], thiourea[38] and aniline[39], a blue colour develops.

According to Swinehart, in the thiocyanate case the colour does not develop if irradiated (using normal tungsten light) SCN^- is mixed with fresh $[(NC)_5FeNO]^{2-}$ or vice versa. Since SCN^- begins to absorb in the ultraviolet at 280 mμ (thiourea 320 mμ) and there is no transmission through pyrex below 360 nm the observed reaction must result from the immediate products of the excitation[40] of $[(NC)_5FeNO]^{2-}$. Swinehart proposed[40] that the blue coloration in the irradiated $[(NC)_5FeNO]^{2-}$ - SCN^- case is due to



$$\left[(NC)_5FeNO\begin{matrix}OH\\SCN\end{matrix}\right]^{2-}$$

and that by cleavage of water the ion is converted to a green complex [37,38]



However, there appears to be no firm evidence to support these assignments[41]. The spectrum for the blue species formed is the same for both thiocyanate and thiourea (λ_{max} = 580-590 mμ)[40]. The maximum closely corresponds to that of $[(NC)_5Fe^{II}NO]^{2-}$. The photochemical course of these reactions may be intimately involved with the fact that excitation with low energy light (long wavelength) involves a transition to a molecular orbital containing primarily the antibonding orbital (π^{*}NO) on the NO^+.

Chemical properties of sodium nitroprusside

The chemical and physical properties of the nitroprusside ion (pentacyanonitrosylferrate(II), $[(NC)_5FeNO]^{2-}$, have attracted considerable interest during various periods in chemical history. Compounds containing $[(NC)_5FeNO]^{2-}$ were characterised in the mid-19th century. At this time and soon afterwards much of the chemistry of the ion was qualitively described. In the period between 1910 and 1930 an Italian group of chemists centered about Cambi, Scagliarini and their co-workers virtually dominated the investigation of the chemistry of the ion. They prepared and characterised a wide variety of compounds which result from reactions between bases and $[(NC)_5FeNO]^{2-}$. These reactions involve the addition of bases to the NO moiety of $[(NC)_5FeNO]^{2-}$, and thus attention has been directed to that functional group.

Although carbanions are formed by addition of hydroxide and, hence consideration of hydroxide and sodium nitropursside need to be described.

An intense yellow colour is obtained by sodium nitroprusside and caustic alkalis or alkaline earth hydroxides.

Cambi and Szego in this investigation of the reaction between sodium nitroprusside and hydroxide ions reported the existance of the equilibrium as

$$\left[(NC)_5FeNO\right]^{2-} + 2\,OH^- \rightleftharpoons \left[(NC)_5FeNO_2\right]^{4-} + H_2O$$

Many groups of workers have determined the equilibrium concentration quotient for this reaction. Values obtained are 1.0×10^6 (298°K, 0.5 m KCl), 0.74×10^5 (293°K), and 1.5×10^6 (298°K, 1.0 m NaCl). The thermodynamic parameters, ΔH^o and ΔS^o are -16.2 ± 0.9 kcal/mole and -26.1 ± 3.0 ev. The equilibrium concentration quotient for this reaction is strongly dependent on the nature and concentration of the inert electrolyte, which explains the slight differences observed: this behaviour is observed for many equilibria involving only negatively or positively charged ions.

The comparison between the equilibrium quotient for this reaction with that of the aqueous equilibrium

$$NO^+ + 2OH^- = NO_2^- + H_2O$$

The equilibrium constant for this reaction is 2.3×10^{31} if a value 5×10^6 (293°K) [37] is used as the equilibrium quotient for the reaction

TABLE 2

Summary of kinetic data for $[(NC)_5FeNO]^{2-}$-OH reactions

Reaction	Rate law	k^a $m^{-1}sec^{-1}$	H kcal/mole	S e. v.
$[(NC)_5FeNO]^{2-} + 2OH^- = [(NC)_5FeNO_2]^{4-} + H_2O$	$k[(NC)_5FeNO^{2-}][OH^-]$	0. 55	12. 6	-17. 5
$[(NC)_5FeNO_2]^{4-} + H_2O = [(NC)_5FeH_2O]^{3-} + NO_2^-$	$k[(NC)_5FeNO_2^{4-}][H_2O]$	1.4×10^{-4}	21. 6	-3. 6
	$k[(CNC)_5FeH_2O^{3-}][NO_2^-]$	0. 46	9. 3	-28. 8

$NO^+ + H_2O = HNO_2 + H^+$. Comparison with the equilibrium quotient for the reaction in which NO^+ is formally bound to an iron(II) centre (approximately 10^6) clearly indicates that NO^+ is highly stabilized against conversion to NO_2^- by OH in $[(NC)_5FeNO]^{2-}$. Also high concentrations of H^+ are required to produce appreciable concentrations of NO^+ from NO_2^-, while $[(NC)_5FeNO]^{2-}$ is a source of NO^+ at low acid concentrations. Hence the $[(NC)_5FeNO]^{2-}$ ion provides a unique opportunity to explore the chemistry of NO^+ under conditions where H^+ is not competing with it for bases sites.

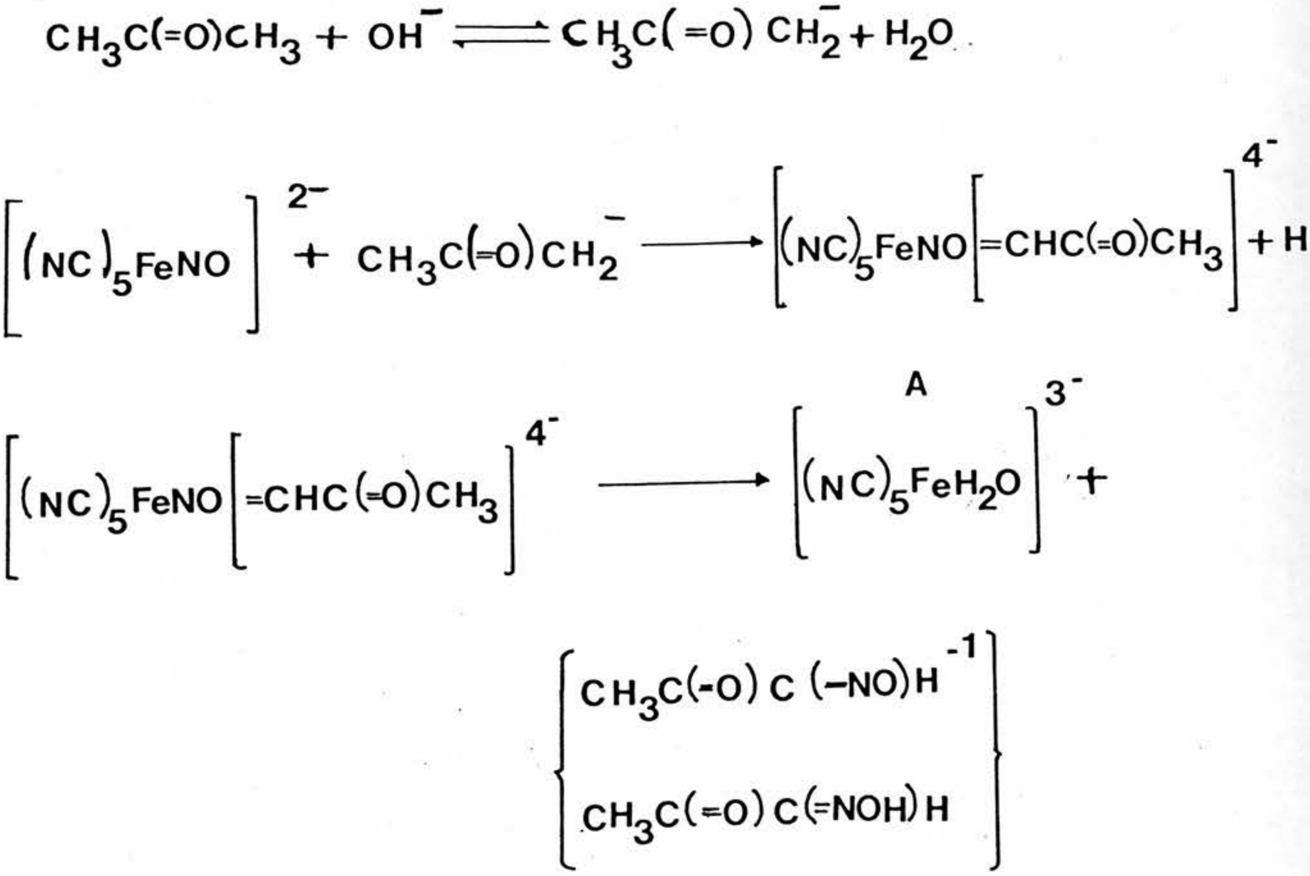
Once $[(NC)_5FeNO]^{4-}$ is produced from the reaction between $[(NC)_5FeNO]^{2-}$ and OH^- the following reaction occurs

$$\left[(NC)_5FeNO_2\right]^{4-} + H_2O = \left[(NC)_5FeH_2O\right]^{3-} + NO_2^-$$

The equilibrium constant for this reaction is $(3.0 \pm 0.1) \times 10^{-4}$ (298°K, 1.0 M NaCl). The thermodynamic parameters ΔH^o and ΔS^o are 12.3 ± 0.2 kcal/mole and 25.2 ± 0.7 ev[39].

Table 2 summarizes the kinetic parameters for the reactions of the $[(NC)_5FeNO]^{2-}$-OH^- system. The rate of formation of $[(NC)_5FeNO_2]^{4-}$ from $[(NC)_5FeNO]^{2-}$ and OH^- is first order in the concentrations of both reactants. A reasonable mechanism would be the slow reaction of a OH^- with $[(NC)_5FeNO]^{2-}$ followed by a rapid reaction in which a OH^- removes an H^+ from the resulting species to yield H_2O and $[(NC)_5FeNO_2]^{4-}$. Oxygen-18[45] exchange and infrared studies on $[(NC)_5FeNO_2]^{4-}$ indicate that the NO_2^- group is bound as the nitro, Fe-NO_2, and not the nitrito, Fe-ONO, ligand.

The chemistry of SNP is indeed interesting because it reacts with



$$CH_3C(=O)CH_3 + OH^- \rightleftharpoons CH_3C(=O)CH_2^- + H_2O$$

$$\left[(NC)_5FeNO\right]^{2-} + CH_3C(=O)CH_2^- \longrightarrow \underset{A}{\left[(NC)_5FeNO\left[=CHC(=O)CH_3\right]\right]^{4-}} + H$$

$$\left[(NC)_5FeNO\left[=CHC(=O)CH_3\right]\right]^{4-} \longrightarrow \left[(NC)_5FeH_2O\right]^{3-} + \left\{\begin{array}{l} CH_3C(-O)C(-NO)H^{-1} \\ CH_3C(=O)C(=NOH)H \end{array}\right\}$$

Scheme 1

many carbanions to give highly coloured complexes of limited stability (see Table 3). Several of the structures of these highly coloured complexes have already been elucidated. The reactions of SNP with a number of carbanions will now be described.

1. Pyruvic acid

Sodium nitroprusside is widely used as a reagent for organic analysis. Copper nitroprusside obtained from it was used in 1857 to detect artificial essential oils, particularly turpentine. Small quantities of pyruvic acid are detected and estimated colorimetrically with sodium nitroprusside, in alkaline solution.

2. Ketone and related compounds

The reactions of sodium nitroprusside with aldehydes and ketones have been studied in detail. If slightly alkaline solutions containing ketones or other compounds containing acidic hydrogen bound to carbon are mixed with $[(NC)_5FeNO]^{2-}$ a coloration (usually red) develops which often rapidly fades to yellow. The resulting solution usually contains $[(NC)_5FeH_2O]^{3-}$ and the oxime of the organic compound. For example, it has been suggested that the sequence of reactions in the $[(NC)_5FeNO]^{2-}$ the propanone system can be represented in Scheme 1[48,49].

Since red salts containing species A have been isolated, this anion is assumed to give rise to the red coloration solution. When species A is treated with acetic acid the solution becomes blue-violet[48]. The equilibrium involved is thought to be[51]

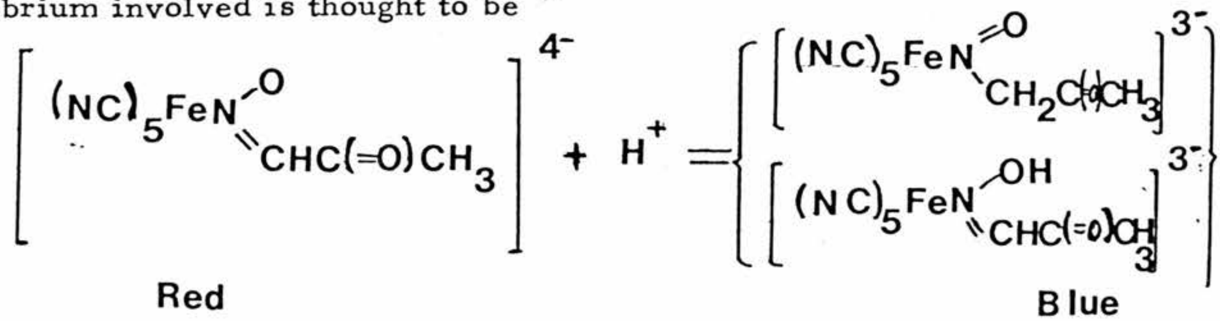


TABLE 3

Reactions of $[(NC)_5FeNO]^{2-}$ with Basic Ligands

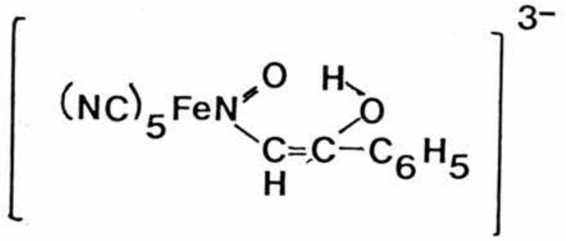
a) Intermediates usually isolated from methanol

b) $[(NC)_5FeH_2O]^{3-}$

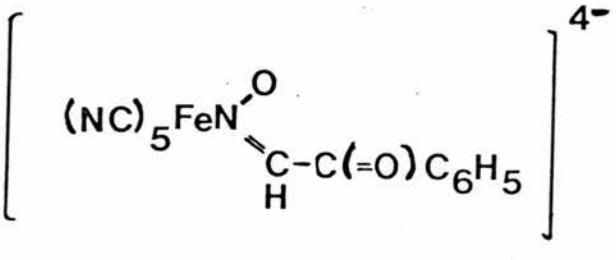
Reactant	Intermediate[a] isolated	Products[b]	References
$CH_3C(=0)CH_3$	$Na_4[(NC)_5FeC_3H_4O_2N]$ red	$CH_3C(=0)C(=NOH)H$	43, 60, 64, 68
$CH_3C(=0)C_6H_5$	$Na_4[(NC)_5FeC_8H_6O_2N].H_2O$ red	$HC(=NOH)C(=0)C_6H_5$	43, 61, 69
$CH_3C(=0)C_6H_4Br$	$Na_4[(NC)_5FeC_8H_5BrO_2N]\cdot H_2O$ red	$HC(=NOH)C(=0)C_6H_4Br$	44, 61, 69
$CH_3C(=0)(H_2C(=0)CH_3$	$Na_4[(NC)_5FeC_5H_6O_3N]$ red	$CH_5C(=0)C(=NOH)C(=0)CH_3$	61
$CH_5C(=0)C(=0)OH$	red salt	$CH(=NOH)C(=0)C(=0)OH$	62
$NCCH_2C(=0)OCH_2CH_3$	unstable red salt	$NCC(=NOH)C(=0)OCH_2CH_3$	52
$NCCH_2C_6H_5$	unstable red salt	$NCC(=NOH)C_6H_5$	62
p-$O_2NC_6H_4CH_2CN$	unstable red salt	p-$O_2NC_6H_4C(=NOH)CN$	62
$CH_3C(=0)CH_2C(=0)OH$	-	red coloration	62, 65
α, β, diketones	-	-	43

The same type of equilibrium has been proposed to account for the variation in colour with pH for a number of $[(NC)_5FeNO]^{2-}$-ketone systems[48]. Cambi and his co-workers first investigated the acetophenone $[(NC)_5FeNO]^{2-}$ system and proposed an equilibrium between species analoguous to those described above to account for the pH dependent colour changes observed.

An infrared investigation has been made on salts of the blue acetophenone complex[50]. On the basis of a medium strength band at 1930 cm^{-1} corresponding to the nitrosyl absorption and a weak carbonyl band at 1684 cm^{-1} the following structure was suggested :



Salts of the red form show no N=O absorption, but bands corresponding to NO^- at 1175 cm^{-1} and 1155 cm^{-1} are observed. The suggested structure is :



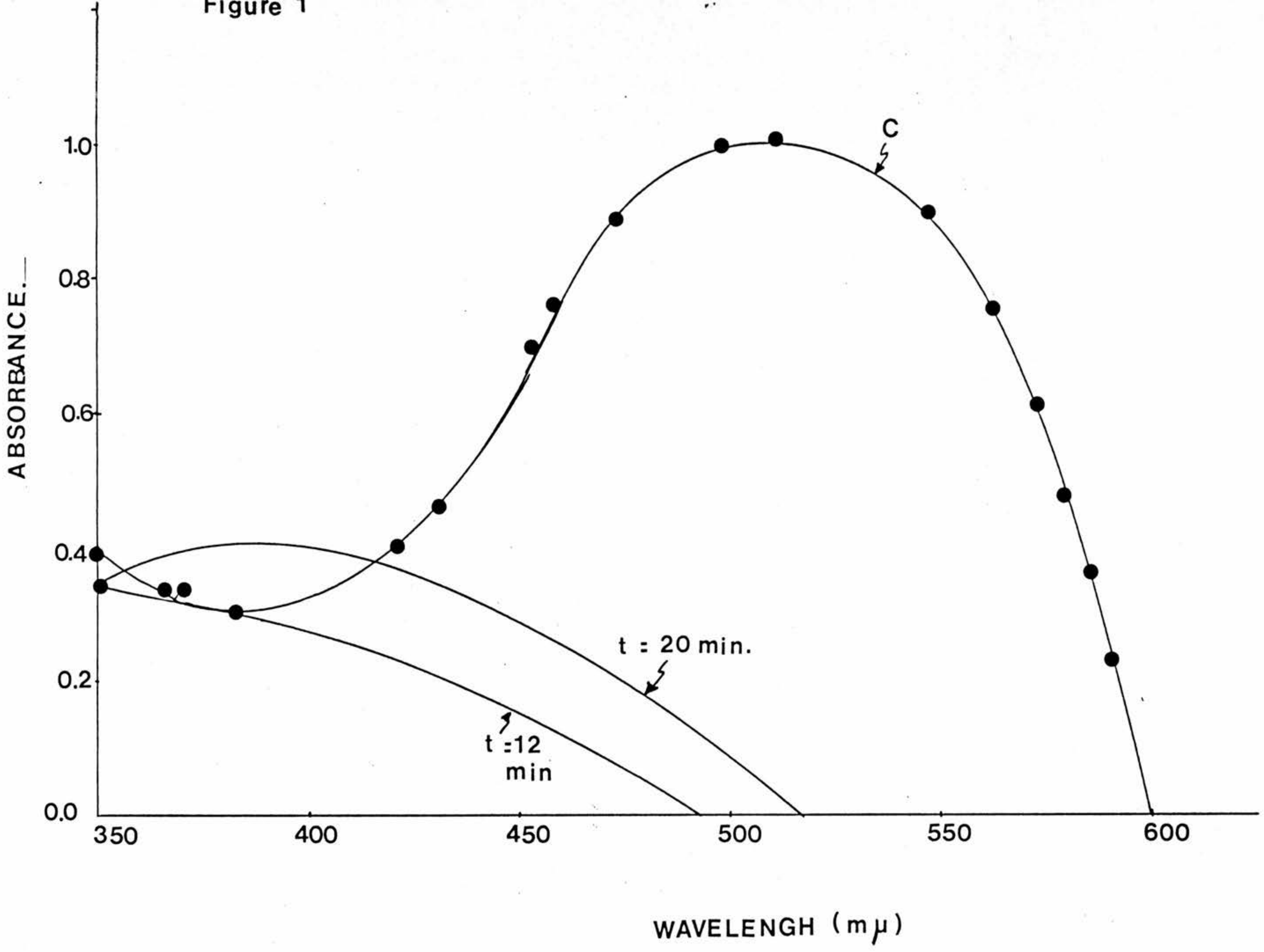
Pavolini[52] has studied a wide variety of reactions between $[(NC)_5FeNO]^{2-}$ and organic compounds. Aldehydes and ketones which are α, or β unsaturated readily react with $[(NC)_5FeNO]^{2-}$ (ionone and citrel) while ketones which are not α, β unsaturated do not react (menthone and citronellal).

FIGURE 1

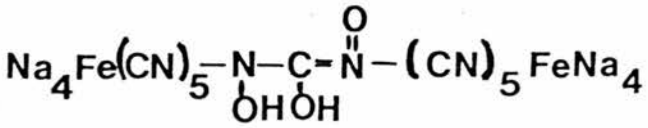
Spectra of solutions obtained at the time immediately, and 12 and 20 minutes after mixing.

C corresponds to the spectrum of $[(NC)_5Fe(C_3H_5NO_2]^{3-}$ and D to a combination of the spectra of $[(NC)_5FeNO_2]^{4-}$ and $[(NC)_5FeH_2O]^{3-}$. The slow change in the spectrum of B is attributed to the formation of some $[(NC)_5FeOH]^{4-}$ and its polymerisation.

Figure 1


ABSORBANCE.
1.0
0.8
0.6
0.4
0.2
0.0
350
400
450
500
550
600
WAVELENGH (mμ)
C
t : 20 min.
t :12
min

Alkaline formaldehyde solution gives an amber[53] colour possibly due to the formation of B.



$Na_4Fe(CN)_5-\underset{OH}{N}-\underset{OH}{C}-\overset{O}{N}-(CN)_5FeNa_4$

B

Propanone does not react with $[(NC)_5FeNO]^{2-}$ unless hydroxide is present[4]. Figure 1 shows the spectrum of a solution ([propanone] = 3. 4 M, $[OH^-]$ 0. 050 M and $[(NC)_5FeNO]^{2-}$ initial = 2. 65 x 10^{-4} M) at various states of reaction. The spectrum of species was obtained by extra polation of curves of absorbance vs. time to zero time at a number of wavelengths. The spectrum of the yellow solution is represented by curves taken at 12 and 20 min after reaction. The kinetics of these reactions have been studied by several workers[49,50,54].

3. Creatinine

A beautiful deep ruby red colour is obtained by alkaline creatinine[56] solution and sodium nitroprusside. However, this will be discussed in detail later on.

4. Malononitrile

The mixing of SNP and malononitrile $CH_2(CN)_2$ in the presence of sodium hydroxide immediately gives an intense red coloration. This will also be discussed in detail later on.

Conclusion

There is no doubt that the reaction between sodium nitroprusside and carbanions in alkaline condition involves addition of the ions to the NO group to give complex anions as seen in the various examples above.

STOPPED FLOW SPECTROPHOTOMETER

INTRODUCTION

HISTORICAL AND GENERAL INTRODUCTION

For many years after the earliest investigation in 1850 the rates of chemical reactions in solution were studied by simple methods. The reaction was initiated by mixing the reagent solutions, and its progress was followed by titrating samples, or making measurements of some physical property, after various intervals of time. The time required for mixing and for observation had to be short compared with the half-time of the reaction. Consequently, the fastest reactions that could be measured had half-times of minutes. Many reactions, especially those of ions were immeasurably fast, and their mechanisms could not be kinetically investigated.

The situation is now entirely altered. The first major advance was the introduction of the continuous-flow method by Hartridge and Roughton[58] in 1923. This made possible the study of reactions with half-times of milliseconds - a reduction of the orders of 10^3 or 10^4 compared with conventional methods. The limiting factor was the rate of mixing. In the years that followed, the method was steadily developed, and was applied to reactions of haemoglobin and enzymes, but it was not at once widely taken up.

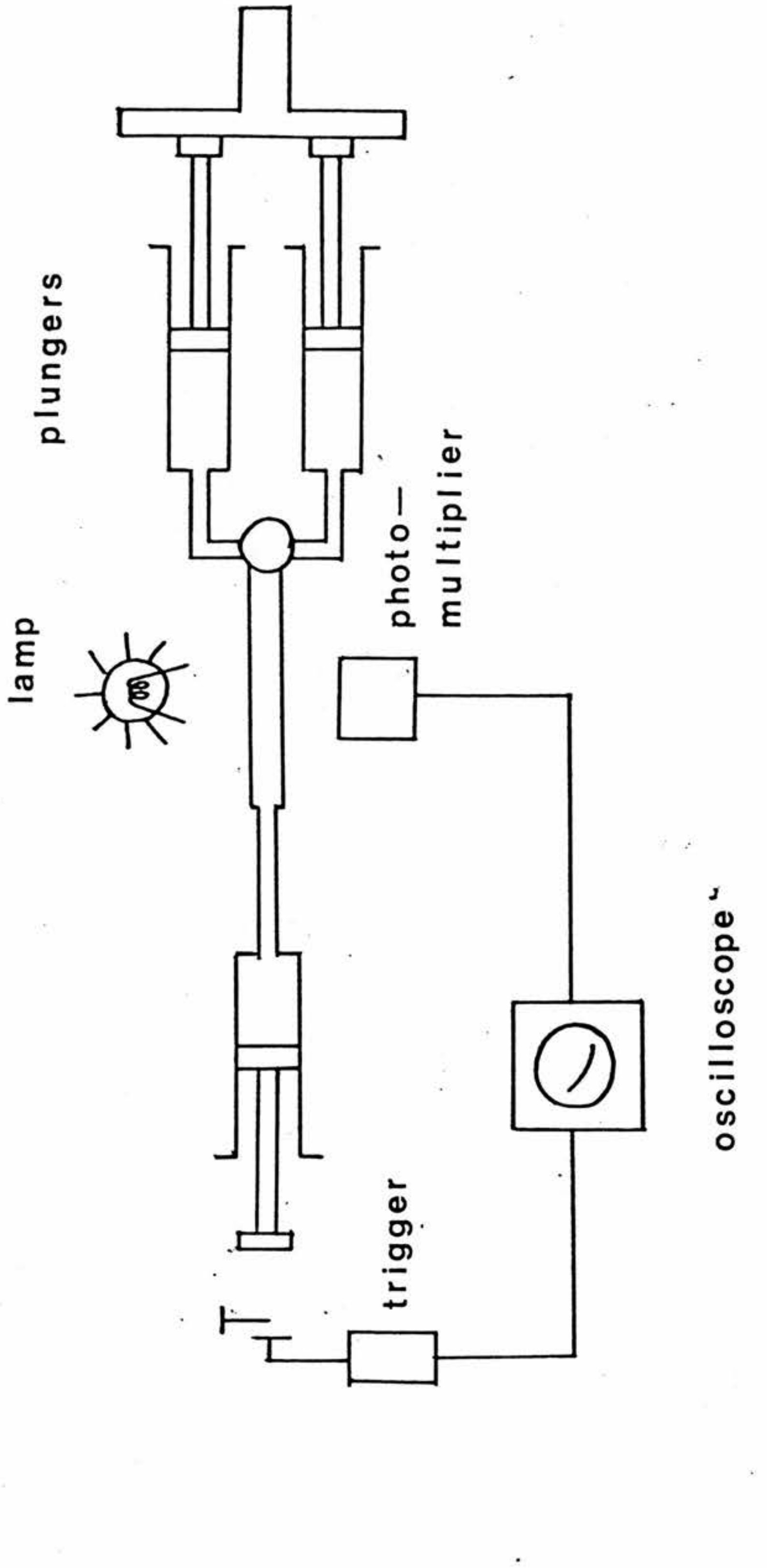
By 1954, however, when the Faraday Society held a discussion on the study of fast reactions, a whole range of techniques had emerged.[59] Some of these were developments of flow methods which made them simpler and more widely applicable. Others were radically different, in that the reaction was not initiated by mixing. Some, such as the temperature-jump and flash techniques, made use of oscilloscopic fast-recording gear. In others, such as the fluorescence and ultrasonic-absorption methods, a steady state was achieved, which could be observed at leisure. In 1959 an international conference on fast reactions in solution was held at Hahneuklee in Germany[60] showed that these new methods were being systematically used and had produced results of great interest. Rate constants can now be measured over the whole range from those accessible to conventional techeniques right up to the highest values conceivable on current theories. The accessible time-range has been extended by something like ten powers of ten.

The meaning of 'fast'. The term 'fast-reaction' is relative, imprecise, and ambiguous, but it is none the less explicable. In its primary sense, it means a reaction that is fast relative to the time required for mixing and observation by conventional methods. A reaction with half-time of a second or less would certainly be fast according to this criterion, though the borderline would depend on the experimental details.

THE STOPPED-FLOW METHOD

Principles

In this technique, two reactant solutions are rapidly mixed by being forced through a mixing chamber, and the mixed solution flows down a tube. The flow is suddenly stopped so that the solution comes to rest within a millisecond or two. The element of solution that comes to rest at (say) 1 cm from the mixing chamber will have been mixed for a few milliseconds. The reaction in this fixed element of solution is followed by making observations at this point, by some rapid method such as photo-



Schematic diagram of stopped–flow spectrophotometer multiplier. The response may be applied to a cathode-ray oscillograph; with the help of a time base, a curve representing the extent of reaction against time may be displayed on the screen. If the reaction is slow enough, a pen recorder may be used, or even visual readings of a meter, or now it can be linked to a microcomputer 'Pet'. The time-peak extends from a millisecond up to several minutes, and is continuous with that available to conventional techniques.

The efficient operation of a stopped-flow apparatus depends on several factors. The reactant solutions must be thoroughly mixed; the mixing-chamber must therefore by properly designed, in the light of the investigations made on continuous flow methods, the flow velocity must be adequate. The observation point must be some millimetres from the mixing chamber to ensure that mixing is complete; but not too far away, since the lost time between mixing and observation must be minimized. Finally, the flow must be stopped very quickly, for the following reason. The efficiency of mixing falls if the flow is too slow, consequently if the rate of flow were to be decreased gradually, the liquid which ultimately came to rest at the observation point might be incompletely mixed and the apparent reaction rate would initially be to low. Moreover, the more sudden the stoppage, the faster the reactions that can be observed.

Practical design for stopped-flow apparatus

The stopped-flow method owes its wide adoption to the stopping device due to Gibson.[62] A small piston at the end of the observation tube is pushed along by the reaction mixture, and is suddenly stopped by coming up against a seating, or an external stop. This simple arrangement is extremely effective. The flow is stopped in 1-2 msec.

The apparatus used by Gibson has been the prototype of most of the stopped-flow machines now in existence. It is shown diagramatically in Fig 1. The reactant solutions are contained in hypodermic syringes (2ml) whose plungers are driven manually by means of a block sliding between guides. The mixing chamber is of perspex and has two sets of four tangentially-arranged jets. The observation tube is 2mm in diameter. It leads to a cylinder with a light perspex piston, which comes up against a seating and so stops the flow. The liquid is observed at a point 8mm from the mixing chamber; the time between mixing and observation, with a flow velocity of about 5 metres per second, is about 3ms. Observations are made photometrically. The light-source is a lamp with filters, or a monochromator, and the detector is a photomultiplier, whose output is applied to a memory oscilloscope with a time-base; the trace on the screen can be photographed. The trace represents a change in the absorbance occurring in the reaction solution. At the same time information is stored in the transcient recorder and from this the rate constants can be calculated for the reaction. The
19 information from the transient recorder is passed into the microcomputer 'Pet' where calculations of the rate constant for the reaction is proceeded. Optical densities recorded are reproducible to about ±1%. Each run requires about 0.15ml of each reactant solution. Reactions with half-times down to a few milliseconds can be studied. The temperature is controlled by immersing the apparatus in a thermostat. The stirrer is switched on so that the temperature throughout the experiment is maintained at isothermal level.

Methods of observation must be adapted to the reaction under investigation. The simple spectrophotometric system described above is adequate for many reactions. If it is essential to use light of a narrow band of wavelengths variable at will, the lamp and filters may be replaced by a monochromator. If reactions lasting more than a few seconds are to be investigated, the light source must be stabilized; and if the highest sensitivity is needed, it may be necessary to provide high-gain amplification. The stopped flow method is not limited to reactions involving colour-changes; besides spectrophotometry, it has been adapted to emf measurements with a glass electrode and to conductivity measurements.

COMPUTER LISTING

```
PRINT  "PRESS PUNCH"
DIMA (50), T (50), K (9), LG (50)
SYS (832)
PRINT
PRINT "ENTER X COORDS. OF USEFUL DATA (TO NEAREST 0.5CM),  X1, X2"
INPUT  X1, X2 :  PRINT
PRINT  "ENTER X COORDS FOR INFINITY VALUE CALC. (TO NEAREST .25CM),  X3, X4"
INPUT X3, X4
PRINT
PRINT  "ENTER TIME BASE OF TRANSIENT RECORDER IN SECONDS"
INPUT T
PRINT
PRINT TAB (13)  "RCALCULATING"
N = (X2-X1) * 4
A0 = X1 * 100 + 12288
K = A0
FOR I = 1 TO 25
A (I) + 0
FOR J = 1TO N
K = K+1
A (I) = A (I) + PEEK (K)
NEXT J
```

```
A (I) + A (I) / N

POKE 59467,  PEEK (59467) OR 1

POKE 59467,  PEEK (59467) AND 227

POKE 59467,  PEEK (59467) OR 1

POKE 59468,  PEEK (59468) AND 31 OR 192

SAMPLE = PEEK (59457)

POKE 59468,  PEEK (59468) AND 31 OR 224
```

All credits and sincere thanks for this computer programme go to Dr B G Cox of Stirling University.

CHAPTER I

Studies of compounds related to sodium nitroprusside

Introduction

The chemistry of sodium nitroprusside has been known for a long time. It has been widely studied. No doubt, one of the main interest of sodium nitroprusside is in the field of pharmacology and some of the related compounds of sodium nitroprusside have been synthesised. Sodium nitroprusside was introduced into therapy in the 1970's as a potent vasodilator, short-acting hypotensive agent. The drug is now widely used to produce hypotension during surgery and in the treatment of severe hypotension, congestive heart failure, and myocardial infarction[62-65].

The advantage of sodium nitroprusside over other hypotensive agents is that, once the administration of sodium nitroprusside is stopped, the blood pressure gradually return to its normal level and does not exceed the threshold level. It has been widely claimed in the past that sodium nitroprusside reacts rapidly with haemoglobin to yield significant amounts of cyanide and a number of deaths have been attributed to this effect[66-68]. However, recent investigation proved this to be incorrect.[72]. The reacting primary photoproduct from nitroprusside is known[69] to be the aquapentacyanoferrate(III) ion $[Fe(CN)_5H_2O]^{2-}$. Their findings suggest that it is not blood which causes cyanide release from nitroprusside but the photolysis of sodium nitroprusside to $[Fe(CN)_5H_2O]^{2-}$; in the absence of light this does not form and no cyanide is observed.

$$\Big[Fe(CN)_5NO \Big]^{2-} \xrightarrow{h\nu} NO + Fe(CN)_5^{2-} \xrightarrow[fast]{H_2O} \Big[Fe(CN)_5H_2O$$

Fe^{II}, d^6, inert.

Fe^{III}, d^5, labil

It could be explained to some extent, why the cyanide ligand is $[Fe(CN)_5H_2O]^{2-}$ is labile while that in $[Fe(CN)_5NO]^{2-}$ is not. The latter contains d^6 Fe(II) and in some complexes the ligands are kinetically inert, while the former contains d^5 Fe(III) and this leads to lability.

The hypotensive action of sodium nitroprusside is generally considered to be associated with the nitrosyl group[70], for sodium nitrite is also a vasodilator[71] and sodium nitroprusside a nitrosating agent[72].

There is a similarity existing between the parent nitroprusside ion and those of the related compounds studied here. There is the nitrosyl group present in each of the compounds under investigation. There are several ways in which the NO group can combine with the metal atoms giving a variety of compounds in which the group may be considered as ranging from the NO^+ through netural NO to NO^-. The infrared stretching frequency of the group is an excellent indicator of the nature of the bonding. Thus NO^+ may absorb as high as 2220 cm^{-1} and NO^- as low as 1045 cm^{-1}. Nitric oxide itself absorbs at 1883 cm^{-1} and examples can be found of NO absorption in complexes at most positions in the range 2000-1606 cm^{-1}.

In sodium nitroprusside and the related compounds of general formula $[MX_5NO]^{n-}$ the central metal may be Fe, Co, Mo, Cr, V, Ru, Re, Os, Ir, Pt and the ligand X may be Cl, Br, I, H_2O, OH, CN, NH_3. The NO group is notionally present as NO^+, examples are $Cs_2[Mo(NO)Cl_5]$, $Cs_2[Mo(NO)Br_5]$.

However, in the immediate past most complexes of this type have been prepared for structural investigations and little is known of their chemistry. Once some of these compounds have been prepared and characterised I propose to examine their photolytic stability and chemistry. What is more, any that are photolytically stable and whose chemistry resemble in some measure that of sodium nitroprusside will be tested pharmacologically for toxicity and hypotensive action.

One of the related compounds to sodium nitroprusside studied is halogenonitrosylmolybdates Mo^{II} complexes by Sabyasachi Sarkar and Achim Muller[72]. In general the complexes of bivalent molybdenum are still poorly understood[73]. It is assumed that several strong π-acceptors as ligands are necessary to stabilise the Mo^{II} d^4 system (as e. g. in $[Mo(CO)_2(dias)I_2]$ or $[Mo(dias)_2Cl_2]$[73]. The preparation of molybdenum(II) complexes can be obtained by using potassium nitrosylpentacyanomolybdate $K_4[Mo(NO)(CN)_5]2H_2O$ as the starting material[74].

Preparation of $K_4[Mo(NO(CN)_5 2H_2O$

A weighed amount of powdered molybdenum trioxide (10g) was added to 20g of cold saturated solution of potassium hydroxide. Distilled water was added with stirring until the solid had dissolved. Potassium cyanide (40g) was made up in the form of saturated aqueous solution and filtered through a glass sinter into the above solution mixture. On addition of hydroxylamine hydrochloride (7. 5g) the colour of the solution turned red. The solution was heated on a water bath and after about 30 minutes some concentrated potassium hydroxide was added. The red colour gradually faded to light yellow and eventually turned violet. As the violet colour darkened the nitrosyl compound precipitated out. The solid was filtered and washed with alcohol and ether. The nitrosyl compound was dissolved in the smallest amount of hot water and washed using 50% potassium hydroxide. The filtrate was left overnight for the deep violet compound to crystallise out. The crystals were washed with alcohol and ether and dried in vacuo. The approximate theoretical yield calculated to be in the region of 40%.

The crystallised compound was hygroscopic and ustable in air giving rise to a lemon yellow colour. However, it was found that the violet compound could be kept under nitrogen where it had an unlimited storage time. In vacuum it could be heated to about 180^{o} without decomposition or the escape of water of crystallisation.

The violet compound was used in the next stage which involved the preparation of halogenonitrosylmolybdates.

Preparation of halogenonitrosylmolybdates

A saturated solution of 2g of $K_4[Mo(NO)(CN)_5].2H_2O$ was refluxed with 30ml concentrated hydrochloric acid for approximately 2 hours until a clear solution was obtained. A solution of 2g of caesium chloride in 20ml concentrated hydrochloric acid was then added. The orange crystals (1) which precipitated were filtered, washed and dried in a vacuum oven potassium hydroxide pellets.

(1)

$$K_4\left[Mo(NO)(CN)_5\right].2H_2O \xrightarrow[CsCl]{HCl} Cs_2\left[Mo(NO)Cl_5\right]$$

[1] Orange cryst

Likewise, the preparation of (3) $Cs_2[Mo(NO)Br_5]$ which was deep red,

$[(C_6H_5)_4P][Mo(NO)Cl_4]$ yellow and of (4) $[(C_6H_5)_4P][Mo(NO)Br_4]$ red were carried out analogously. However, (1) and (3) were interconvertible in hydrochloric acid according to the following equation.

(2)

$$Cs_2[Mo(NO)Cl_5] \xrightleftharpoons[CsCl]{[(C_6H_5)_4P]^+} [(C_6H_5)_4P][Mo(NO)Cl_4]$$

[1] [3]

(3)

$$K_4[Mo(NO)(CN)_5]\cdot 2H_2O \xrightarrow[CsBr]{HBr} Cs_2[Mo(NO)Br_5]$$

deep red.

(2)

$$K_4[Mo(NO)(CN)_5]2H_2O \xrightarrow[{[(C_6H_5)_4P]Cl}]{HCl} [(C_6H_5)_4P][Mo(NO)Cl_4]$$

yellow.

(4)

$$K_4[Mo(NO)(CN)_5]2H_2O \xrightarrow[{[(C_6H_5)_4P]Br}]{HBr} [(C_6H_5)_4P][Mo(NO)Br_4]$$

The Mo^{I} compound $Cs_2[Mo(NO)Cl_4.H_2O]$ containing the $[MoNO]^{2+}$ group was isolated as stable green crystals by a new method for the reduction of nitrosyl complexes[75].

$$Cs_2[Mo(NO)Cl_5] \underset{\text{conc. } HCl/Br_2.}{\overset{\text{dil. } HCl/Mg.}{\rightleftharpoons}} Cs_2[Mo(NO)Cl_4H_2O]$$

[2] orange. [3] green.

(Reduction and simultaneous substitution due to the strong trans-effect of NO). Compound [3] can be reconverted into [2] by 'oxidation' and has been characterised by elemental analysis.

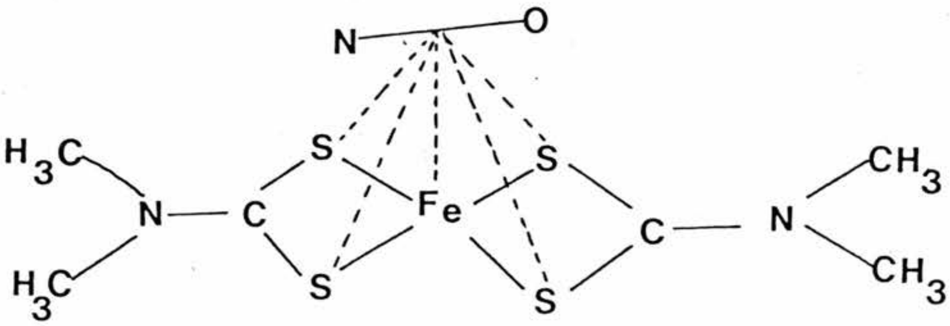
Preparation of $Cs_2[Mo(NO)Cl_4.H_2O]$

Aquahalogenonitrosylmolybdate (1g) was dissolved in 20ml 3N hydrochloric acid. 0.14g Mg powder was added in the cold. On addition of methanol (10ml) green crystals of $Cs_2[Mo(NO)Cl_4H_2O]$ separated out slowly.

Preparation of $Fe(NO)(S_2CN(C_2H_5)_2)_2$

Ferrous sulphate (5.0g) and sodium nitrite (0.5g) were dissolved in 25g 2M sulphuric acid. To this was added quickly 10g of sodium diethyldithiocarbamate with stirring. The solution was stirred vigorously for 5 min. The complex was extracted with chloroform (3 x 20 cm^3). It was dried over anhydrous calcium chloride. The solution was filtered and the filtrate was allowed to evaporate in a basin to obtain crystals of the complex. Black crystals were collected by filtration.

Structure of nitrosylbis(dimethyldithiocarbamato) iron[78](I)



Potentiometric precipitation titrations

Methods

Halogen analyses were carried out potentiometrically using an adaptation of the method described by Lingane.[77] A description of the method developed is as follows:- Approximately 50mg of the sample was accurately weighed into a stoppered 50ml quickfit conical flask, the addition of the sample being made in the dry box. The sample was then hydrolysed with 20ml of 2 M NaOH, the hydrolysis being performed in a closed system to prevent the possible escape of hydrogen halide. The resultant solution or suspension was left to stand for one hour before boiling for a minimum of fifteen minutes to ensure complete hydrolysis. It was then cooled and made just acidic with concentrated sulphuric acid before immediately bubbling sulphur dioxide gas, through the solution for two minutes to reduce any hypohalite ion present. Further boiling served both to drive off excess sulphur dioxide and to reduce the bulk of the solution. After cooling, the solution was neutralised with concentrated ammonia. It was then thoroughly washed with distilled water into a 100ml beaker, 2.5g Anala R barium nitrate was added, followed by 10ml of Anala R acetate and 3-5 drops of boiled out 6M nitric acid, before titrating against 0.1M silver nitrate. The solution was stirred throughout the titration by the use of a magnetic stirrer.

A silver wire was used as an indicator electrode and a saturated Calomel electrode as the reference electrode with a salt bridge containing 3M ammonia nitrate solution.

The barium nitrate was added to remove sulphate ion present and also to help to prevent the absorption of halide ion, especially in the case of iodide, as the silver halide precipitate. The acetone reduces the solubility product of the silver halide being precipitated and results in sharper end-points. Finally, it was found especially in the case of iodide that addition of more than a few drops of 6M nitric acid resulted in the oxidation of the halide to halogen, giving low results. The electrode potential (mV) of the initial halide solution was determined and corresponding measurements taken at 0.1ml intervals of silver nitrate until the end-point was being approached. This was detected by a more rapid increase in the charge in potential and when this was observed, the addition of silver nitrate solution were reduced to 0.2ml for each reading.

A graph of mV readings against ml of silver nitrate added was plotted, the points of inflection being regarded as the end-points of the titration (see graphs 1, 2, 3).

Before each titration the silver wire indicator electrode was cleansed by immersing in 50% nitric acid for one minute, washed with distilled water then immersed in concentrated ammonia for two minutes before a final thorough washing with distilled water.

Good analytical data were not obtained for some of the compounds reported in this research partly because of the inherent instability of these compounds at room temperature and partly because of experimental difficulties. Mechanical stirring is very desirable in precipitation titration to accelerate the attainment of solubility equilibrium.

(a) 0.1M $AgNO_3$ solution.

(b) Reference electrode.

(c) Salt bridge.

(d) Ammonium nitrate solution.

(e) Ammonium nitrate solution.

(f) Magnetic stirrer.

(g) Magnetic bar.

(h) Silver wire electrode.

(i) Thermometer.

Diagrammatic illustration of potentiometric precipitation titration.

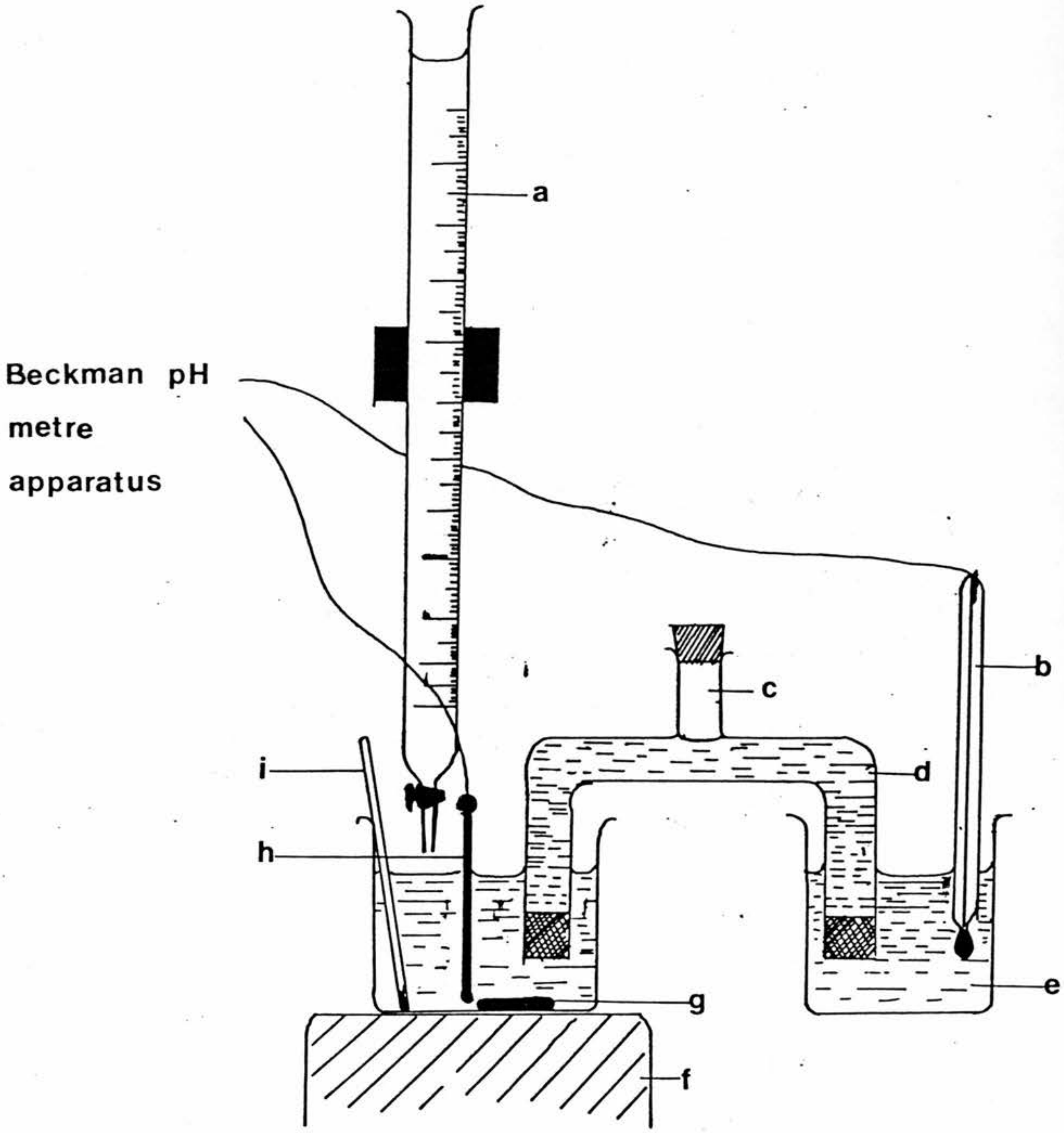


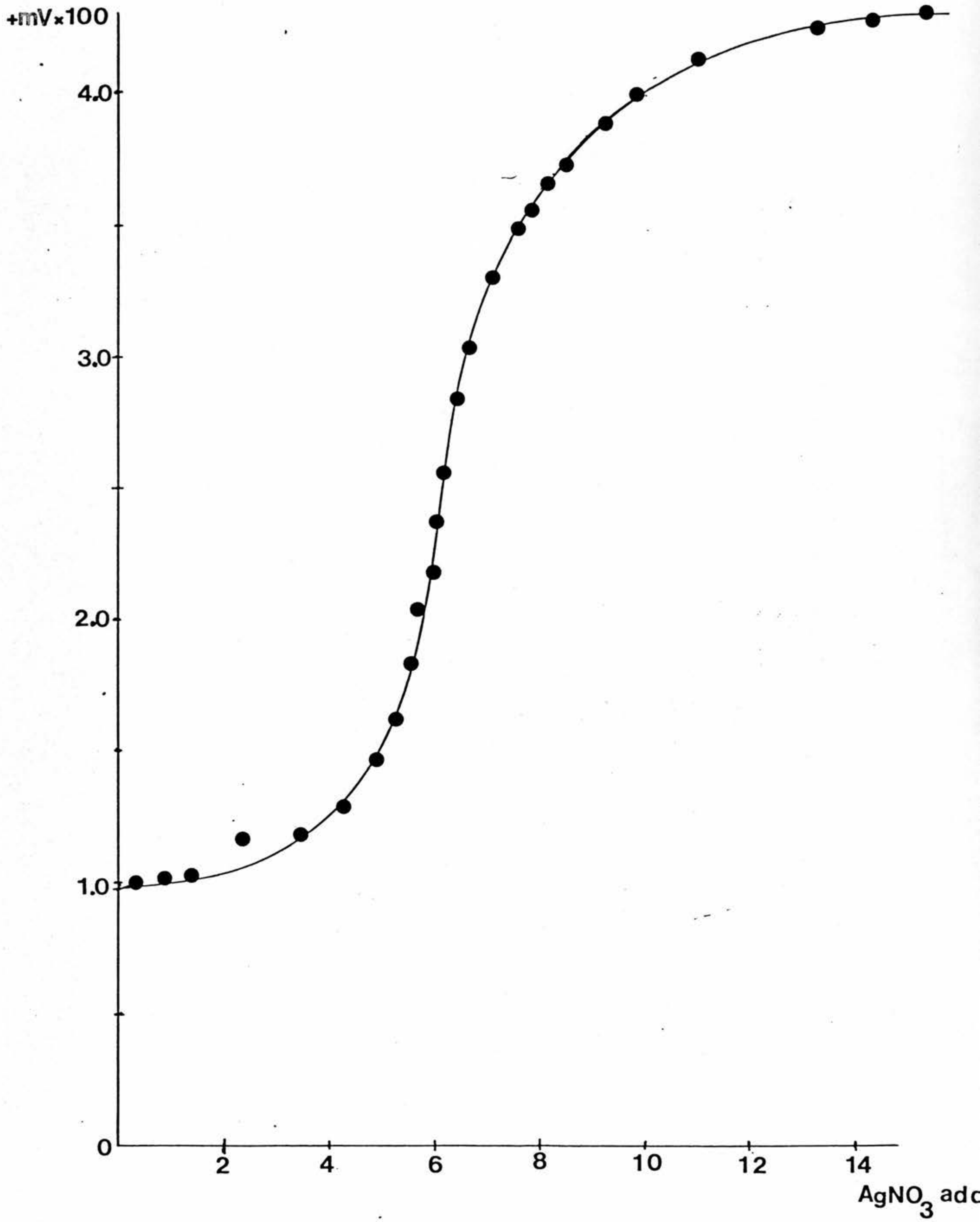
TABLE 4

Potentiometric precipitation titration 80mg of $Cs_2Mo(NO)Cl_5$

$AgNO_3$ added in mls	E. M. F. + mV x 100	temp °C
0.01	1.0400	21°C
1.10	1.0795	"
1.70	1.1025	"
2.20	1.1405	"
2.27	1.2665	"
4.30	1.3220	"
4.50	1.3520	"
5.00	1.4195	"
5.70	1.5710	"
5.90	1.6540	"
6.00	1.7240	"
6.20	2.010	"
6.40	2.035	"
6.60	2.060	"
6.8	2.080	"
7.0	2.095	"
7.2	3.212	"
7.5	3.436	"
7.7	3.524	"
7.9	3.576	"
8.2	3.692	"
8.6	3.805	"
8.9	3.834	"
9.1	3.901	"
9.6	3.932	"
9.9	4.068	"
10.1	4.144	"
12.7	4.226	"
14.0	4.269	"
15.0	4.319	"
20.1	4.410	"

Graph 1

A graph of mV readings against ml. of silver nitrate.



Prodedure

80mg of $Cs_2Mo(NO)Cl_5$ (orange crystals) was weighed out. This was proceeded to the potentiometric precipitation titrations.

Calculation and Results

Calculation of the orange compound from the graph gave the following results :

Found Cl In
$Cs_2Mo(NO)Cl_5$ = 31.06%

Requires Cl in
$Cs_2Mo(NO)Cl_5$ = 31.19%

TABLE 5

Potentiometric precipitation titration using $Cs_2Mo(NO)Cl_4.H_2O$ (70mg) titrating against 0. 1 M $AgNO_3$

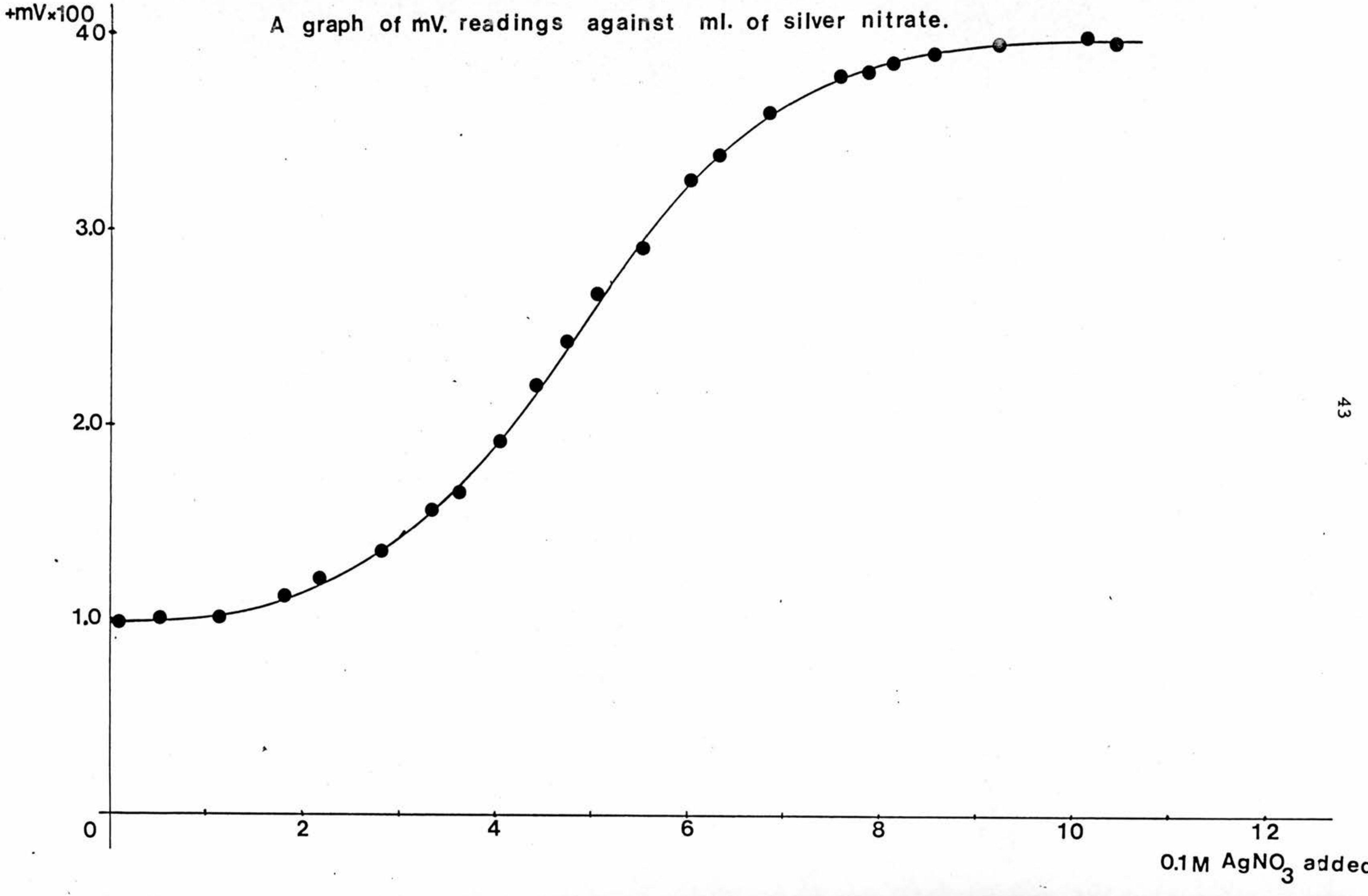
Mls of $AgNO_3$ added	E. M. F. (+ mV + 100)	temp° of solution
0. 05	0. 8300	23°C
0. 10	0. 9975	"
0. 45	1. 0320	"
1. 05	1. 1220	"
1. 50	1. 1700	"
1. 65	1. 2140	"
1. 90	1. 2580	"
2. 40	1. 3242	"
2. 75	1. 3845	"
3. 1	1. 5480	"
3. 6	1. 7390	"
3. 75	1. 8161	"
4. 04	1. 9345	"
4. 10	2. 0160	"
4. 30	2. 1105	"
4. 45	2. 2450	"
4. 60	2. 3295	"
4. 75	2. 3995	"
4. 85	2. 5395	"
5. 00	2. 7000	"
5. 15	2. 8450	"
5. 30	2. 9770	"
5. 50	3. 1060	"
5. 60	3. 1795	"
5. 75	3. 2820	"
5. 95	3. 3900	"
6. 15	3. 4645	"
6. 45	3. 5520	"

TABLE 5 (continued)

6.95	3.8300	23°C
7.65	3.8950	"
7.80	3.9050	"
8.30	4.0095	"
9.25	4.0810	"
10.15	4.1560	"

Graph 2

A graph of mV. readings against ml. of silver nitrate.



Procedure

70mg of $Cs_2Mo(NO)Cl_4H_2O$ (green crystals) was weighed out. It was proceeded onto the potentiometer precipitation titrations.

Calculation and Results

Calculation of the green compound from the graph gave the following results :

Found Cl in
$Cs_2Mo(NO)Cl_4H_2O$ = 25.05%

Requires Cl in
$Cs_2Mo(NO)Cl_4H_2O$ = 25.7%

TABLE 6

Potentiometric precipitation titration of 77mg of $Cs_2Mo(NO)Br_5$ against silver nitrate

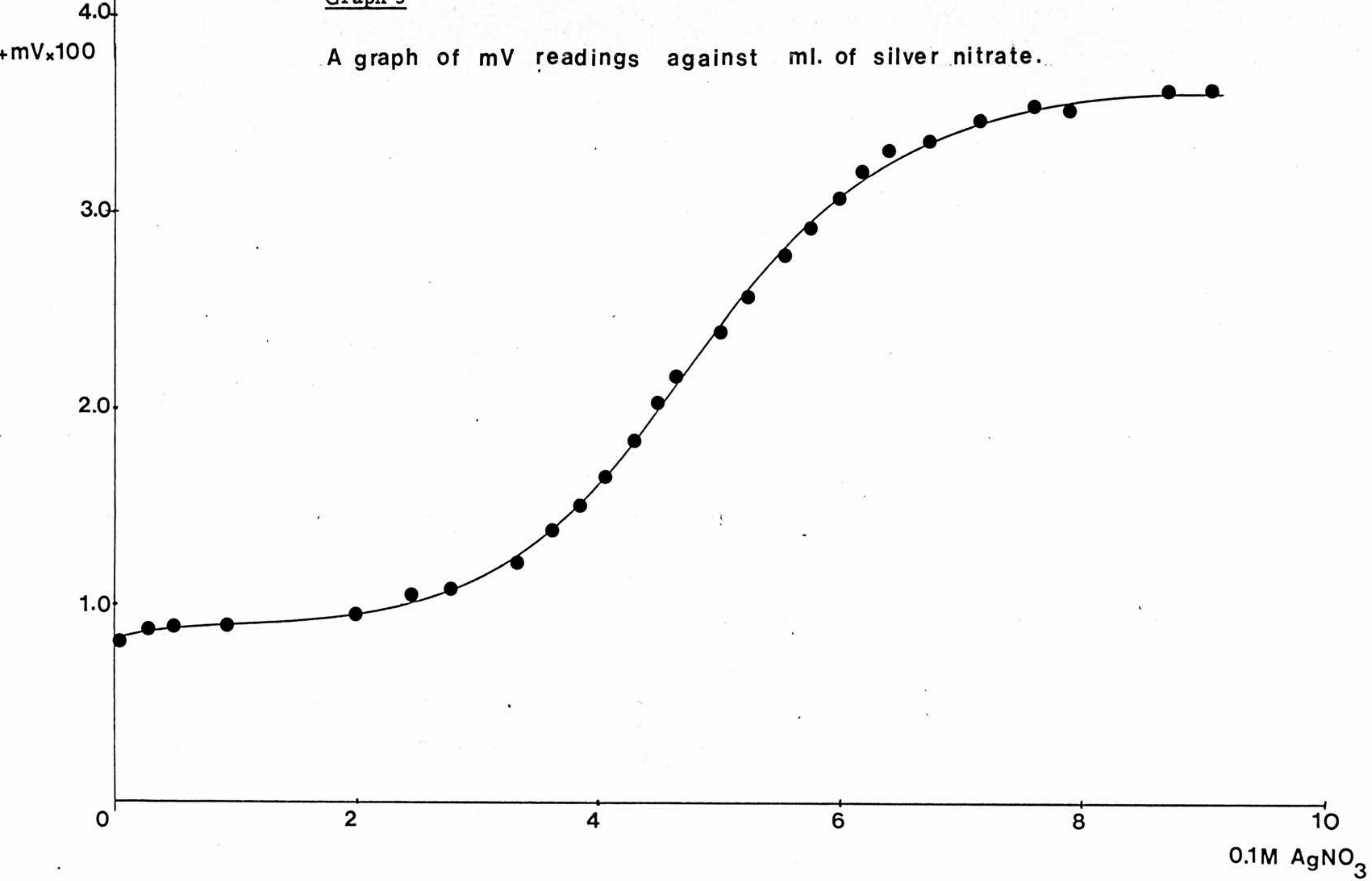
$AgNO_3$ added in mls	E. M. F. Mv x 100	Temperature in °C
0.05	0.7880	23°C
0.10	0.8525	"
0.4	0.9060	"
0.95	0.9620	"
1.75	1.0320	"
2.35	1.1090	"
2.85	1.186	"
3.2	1.254	"
3.65	1.3825	"
3.95	1.4890	"
4.25	1.6360	"
4.5	1.8010	"
4.7	1.966	"
4.95	2.122	"
5.1	2.252	"
5.3	2.416	"
5.45	2.570	"
5.5	2.652	"
5.6	2.778	"
5.65	2.864	"
5.75	2.994	"
5.8	3.080	"
5.9	3.1865	"
6.05	3.2990	"
6.25	3.4400	"
6.45	3.470	"
6.70	3.556	"
7.00	3.642	"

TABLE 6 (continued)

7.55	3.720	23°C
8.3	3.822	"
8.85	3.892	"
9.6	3.958	"
11.25	4.061	"
12.7	4.139	"

Graph 3

A graph of mV readings against ml. of silver nitrate.



Procedure

77mg of $Cs_2[Mo(NO)Br_5]$ (deep red crystals) was weighed out. It was proceeded to the potentiometric precipitation titration.

Calculation and Results

Calculation of the red compound from the graph gave the following results :

Found Br in
$Cs_2[Mo(NO)Br_5]$ = 49.81%

Requires Br in
$Cs_2[Mo(NO)Br_5]$ = 50.59%

Metal analysis

In the molybdenum determination it was not possible to get an accurate enough result from the Atomic Absorption. This was partly due to the presence of the interfering caesium and also experimental difficulties. It was best to carry out the molybdenum determination by Gravimetric methods. The method came from Arthur I Vogel involving the use of α-benzoinoxime (cupron).

Methods

The weighed amount of molybdenum complex was dissolved in concentrated nitric acid and boiled vigorously for ten minutes and left to cool at room temperature. This served the purpose of increasing the oxidation state of molybdenum from 2^+ to 6^+.

A solution was prepared containing 10ml of concentrated sulphuric acid in a volume of 200ml and not more than 0. 15g of sexivalent molybdenum.

The boiling was continued until the odour of sulphur dioxide could no longer be detected. It was cooled to 5-10°C, stirred and slowly 10ml of a solution of the reagent (2g of α-benzoinoxime in 100ml of alcohol) was added and 5ml extra for each 0. 01g of Mo present (from two to five times the theoretical amount was required). The stirring was continued just sufficient bromine water was added to tint the solution a pale yellow and then 4-5ml more of the reagent was added. The mixture was allowed to stand for 10-15 minutes at 10-15°C with occasional stirring and filtered through a Whatman No 40 or 540 filter paper. The precipitate was washed with 200ml of cold freshly prepared wash solution (containing 10ml of the reagent and 2ml of concentrated sulphuric acid diluted to 200ml). The paper was transferred and washed the precipitate to a weighed platinum crucible, the paper was charred at a low temperature without inflaming, and then ignited to constant weight at 500-525°C. It was weighed as molybdenum trioxide MoO_3.

Calculation

Percentage of molybdenum found = 16.07

Percentage of molybdenum calculated = 16.67

Caesium determination

This was carried out using Atomic Absorption technique. The apparatus was that of Perkin-Elmer. The standard stock solution was made by dissolving 1.267 of caesium chloride, CsCl in 1 litre of deionized water or else 0.1267g in 100mls.

However, because caesium has a lower ionization potential than any other metal and a significant portion of the caesium atoms in most flames would be ionized, particularly at the high temperature of the acetylene flame. Therefore, another alkali metal salt was added to both standards and samples to achieve accurate results. The slightly lower temperature air-hydrogen flame produced far less ionization than air-acetylene and it was preferred on that account.

Calculation

i) $Cs_2Mo(NO)Cl_4 . H_2O$

Percentage of caesium found = 46.8%

Percentage of caesium calculated = 47%

ii) $Cs_2Mo(NO)Cl_5$

Percentage of Caesium found = 46.1%

Percentage of caesium calculated = 46.8%

Microanalysis

The analysis confirmed the presence of nitrogen in $Cs_2Mo(NO)Cl_5$.

Required analysis	N = 3.1%
Found	N = 3.01%

Discussion and Conclusion

So far the related compounds to sodium nitroprusside studied have been successfully synthesised and analysed. However, under investigation it was found that the halogenonitrosylmolybdate was unstable in solution forming a blackish oxide which eventually precipitated down. This was undesirable and unsuitable for further kinetic work as it would clog the capillary tubes in the stopped-flow spectrophotometer.

It was found that nitrosylbis(diethylthiocarbamate)iron(I) did not show any sign of reaction with such reagents as hydrochloric acid, sul-

TABLE 7

Reagents	Water	HCl	NaOH	Ethanol	Acetone	Chloroform	Ether
Reactants							
$Cs_2Mo(NO)Cl_5$	Very soluble but blackish oxide ppt down with time	Soluble giving a green solution	Soluble giving a clear solution	Insoluble	Insoluble	Insoluble	Insoluble
$Fe(NO)(S_2CNEt_2)_2$	Soluble giving dark solution	Insoluble	Insoluble	Soluble	Very soluble	Very soluble	Sparingly soluble
NaHS	Very soluble	Very soluble giving white ppt	Soluble	Soluble especially when heated	Very soluble forming white ppt	Insoluble	Insoluble
Thiourea	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble

phuric acid, sodium hydroxide, ethylamine, and sodium hydrogen sulphide . One main difficulty in studying these compounds was finding a solvent which would dissolve both reactants (see Table 7). The experiments carried out between each reactant was done on the SP 800B Ultraviolet spectrophotometer.

The attempts to find any similarity of these related compounds and sodium nitroprusside in terms of chemical and physical properties proved to be inconclusive.

CHAPTER 2

Kinetic studies of the reaction between creatinine and sodium nitroprusside.

INTRODUCTION

The reaction of sodium nitroprusside with creatinine, in the presence of sodium hydroxide immediately gives a red coloration. However, the red coloration gradually fades and the solution becomes yellow. The fact that this colour is only developed with addition of alkali suggests that it is a reaction between the creatinine carbanion and sodium nitroprusside. It is well-known that carbanions do react with sodium nitroprusside, so that on this assumption this explanation is quite reasonable. The rate of this reaction is such that it is suitable for study using stopped-flow spectrophotometry. Formation of the coloured product was followed by measuring the optical density at 470 nm as a function of time. Trial runs were conducted at first using fresh reactant solutions in the two syringes. The solution in each helix was allowed to equilibrate and come to the same temperature as that of the water in the bath before the actual runs were carried out. The stopped-flow spectrophotometer was connected via a transient recorder to the plotter where the observed rate constants were calculated by applying Kezdy-Swinbourne plot technique. This method was carried out for all creatinine reactions.

Procedure :-

Creatinine and sodium hydroxide were placed in one arm of the stopped-flow spectrophotometer while in the other arm was placed sodium nitroprusside. The concentration of sodium nitroprusside was made up to 0.01 M and the concentration of creatinine and sodium hydroxide were made ten times greater.

The effect of ionic strength on the rate constants

The effect of changing the ionic strength upon the rate of reaction was examined by adding potassium chloride at various concentrations to a mixture of 0.2 M creatinine and 0.1 M sodium hydroxide while sodium nitroprusside was kept constant at 0.01 M throughout the experiment at 20°C. This experiment was repeated several times, with the increased temperatures (25°C, 30°C, and 35°C) as shown in Table 8.

TABLE 8

The effect of potassium chloride concentration on the value of k_{obs} at various temperatures

[SNP] = 0.010 M

	k_{obs}/s^{-1}			
[KCl]/M	20°C	25°C	30°C	35°C
0	0.30	0.35	0.40	0.46
0.1	0.32	0.38	0.47	0.56
0.3	0.37	0.44	0.55	0.77
0.5	0.45	0.58	0.70	0.92
0.7	0.45	0.63	0.90	1.03

It can be clearly seen that changing the ionic strength does have a slight effect upon the rate constant. However, this effect is small enough to be neglected for the purposes of this discussion.

The concentration of creatinine carbanion is a crucial factor and this is calculated in all cases by applying the following quadratic equation.

Calculation for Creatinine carbanion

$$\mathrm{CrNH} + \mathrm{OH}^- \overset{K}{\rightleftharpoons} \mathrm{CrN}^- + \mathrm{H_2O}$$

$$K = \frac{[\mathrm{CrN}^-]}{[\mathrm{CrNH}][^-\mathrm{OH}]}$$

$$K_a = \frac{[\mathrm{CrN}^-][\mathrm{H}^+]}{[\mathrm{CrNH}]}$$

$$K_w = [\mathrm{H}^+][^-\mathrm{OH}]$$

$$\therefore\ K = \frac{K_a}{K_w}$$

$$[\mathrm{CrN}^-] = \frac{K_a}{K_w}\left([\mathrm{CrNH}]_t - [\mathrm{CrN}^-]\right)\left([\overline{\mathrm{OH}}]_t - [\mathrm{CrN}^-]\right)$$

The problem is that the variation of K_a with temperature is not known.

For nitromethane[79], the following results were obtained :-

temp °C	10	18	25
$10^{11}K$	3.55	4.66	6.15

Also K_w varies with temperature :-

temp °C	20	25	30	35	40
$10^{14}\ K_w$	0.681	1.007	1.469	2.089	2.917

Both increase and so the ratio of K_a/K_w will, to a first approximation, remain constant.

According to Wollenberger[80] at 22°C $pK_a = 13.4$, hence $K_a = 3.98 \times 10^{-14}$.

$\therefore\ K = K_a/K_w = 3.98$

Sample calculation

$$[OH]_t/M = 0.05 \quad [CrNH]_t/M = 0.10$$

$$K\,([CrNH]_t[OH]_t + [CrN^-]^2 - [Cr\bar{N}][CrNH]_t - [Cr\bar{N}]\,[O\bar{H}]_t) = [CrN^-]$$

$$3.98\,(0.10 \times 0.05 + [CrN^-]^2 - 0.10\,[CrN] - 0.05\,[CrN^-]) = [CrN^-]$$

$$0.0199 + 3.98\,[CrN^-]^2 - 0.597\,[CrN^-] = [CrN^-]$$

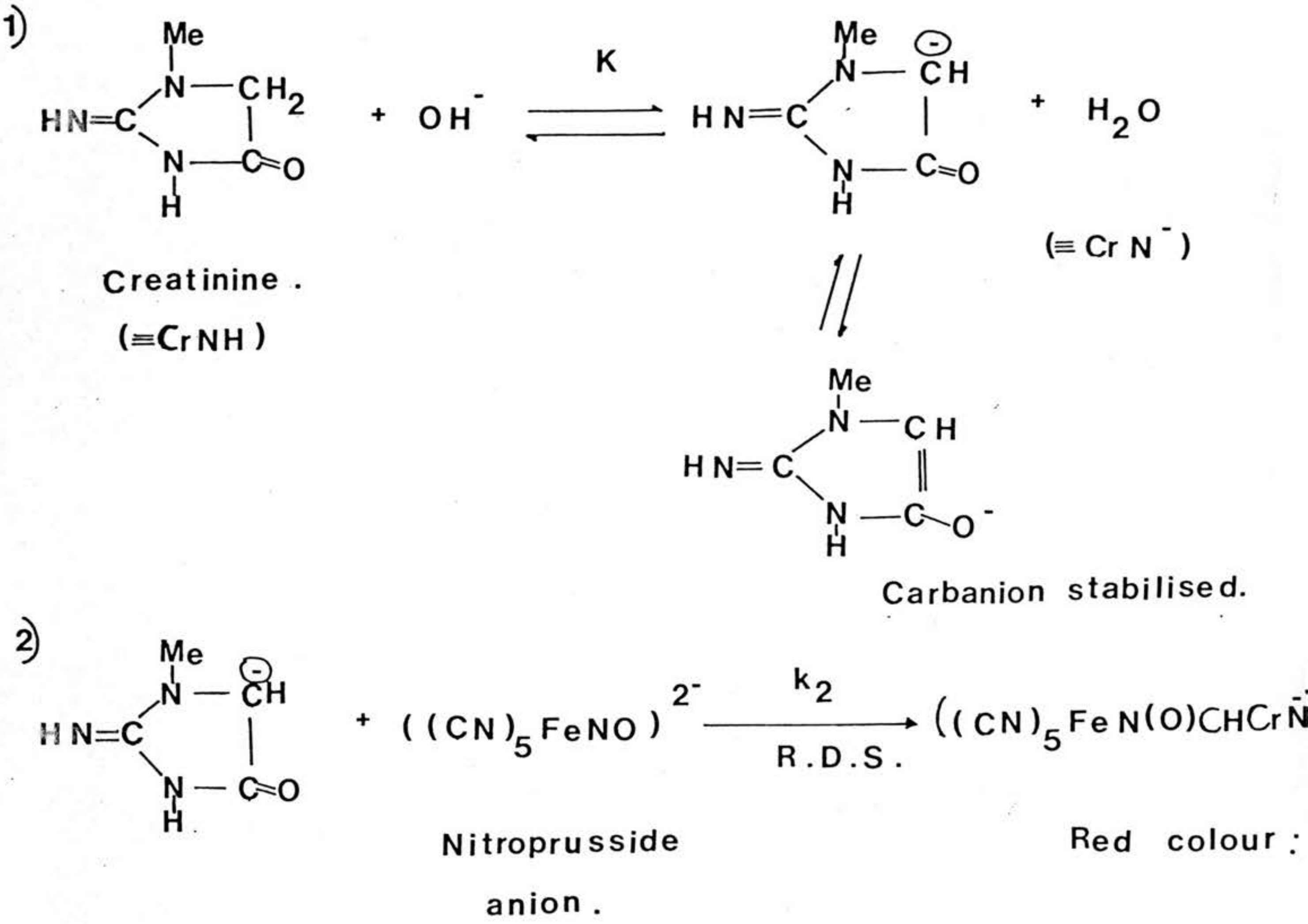
$$\underline{[CrN^-] = 0.013M}$$

The following results are obtained for the equilibrium concentrations of creatinine carbanions as shown in Table 9.

TABLE 9

Concentration of creatinine carbanion

$[OH]_t/M$	0.10	0.10	0.10	0.10	0.10
$[CrNH]_t/M$	0.050	0.10	0.20	0.30	0.40
$[CrN^-]_e/M$	0.013	0.023	0.039	0.050	0.058



Scheme 2

The creatinine carbanion will react with sodium nitroprusside to give a red coloration and it is this which is the rate-determining step (k_2).

The term $[CrNH]_t$ is the molarity of creatinine added and $[NaOH]_t$ is the total concentration of sodium hydroxide added. $[CrNH]_e$ is the equilibrium concentration of creatinine carbanion and $[OH^-]_e$ is the equilibrium concentration of the hydroxide.

RESULTS AND DISCUSSION

The first series of experiments was carried out initially at 20°C in which the total concentration of creatinine was varied from 0.05M to 0.40M with total concentration of sodium hydroxide remaining constant. Pseudo first order rate constants k_{obs} were found for each of a series of reactions as shown in Table 10. The kinetic data were plotted against the equilibrium concentration of creatinine carbanion as presented in Graph 4, page 72.

The second series of experiments was carried out also at 20°C in which the total concentration of sodium hydroxide was varied from 0.05M to 0.4M with total concentration of creatinine remaining constant. The results are shown in Table 11. The values of k_{obs} were plotted against the equilibrium concentrations of creatinine carbanions as shown in Graph 5, page 73.

Both graphs show that they are linear, therefore suggesting that it is a first order in creatinine carbanion and also first order in nitroprusside anion.

The essential point noticeable from these plots of k_{obs} against the equilibrium concentrations of creatinine carbanions was that a linear graph was obtained which ever reactant was varied.

The reason for the dependence of k_{obs} on $[CrHN]_t$ is because creatinine is a weak acid hence k_{obs} appears to be proportional to $[CrNH]_t$ and $[OH^-]_t$.

The values of k_{obs} for varying in the concentrations of creatinine are displayed in Table 10.

TABLE 10

Variation of k_{obs} with creatine concentration at 20°C

$[CrNH]_t$/M	$[NaOH]_t$/M	$[CrN^-]_e$/M	k_{obs}/s^{-1}
0.050	0.10	0.00	0.136
0.10	0.10	0.023	0.208
0.20	0.10	0.039	0.288
0.30	0.10	0.050	0.480
0.40	0.10	0.058	0.578

The values of k_{obs} for varying in the concentration of sodium hydroxide are displayed in Table 11.

TABLE 11

Variation of k_{obs} with sodium hydroxide concentration at 20°C

[SNP] = 0.010 M

$[CrNH]_t$/M	$[NaOH]_t$/M	$[CrN^-]_e$/M	k_{obs}/s^{-1}
0.10	0.05	0.013	0.12
0.10	0.10	0.023	0.32
0.10	0.20	0.039	0.55
0.10	0.30	0.050	0.83
0.10	0.40	0.058	1.14

The last point on these graphs is considerably off. This is probably due to the error involved in subtracting the equilibrium concentration of creatinine carbanion (CrN^-) from the total concentration of creatinine (CrNH) becoming significant as the difference gets small.

A mechanism which is consistent with the observed kinetic is shown in Scheme 2. The first step in the scheme represents an equilibrium formation of the creatinine carbanion (CrN^-) from creatinine (CrNH) and sodium hydroxide (OH^-) by removal of a proton. The equilibrium constant for this step is K. The second step is the rate-determining step which involves the attack of the carbanion on the nitroprusside anion to give a second order rate constant k_2 resulting in the red coloration. The rate equation for this reaction is therefore given by

$$\text{Rate} = k_2 [CrN^-][NP^{2-}]$$

However, the reaction was studied under pseudo first order conditions with $[CrN^-] \gg [NP^{2-}]$

$$\text{so rate} = k_{obs} [NP^{2-}]$$
$$k_{obs} = k_2 [CrN^-]$$

So if the proposed mechanism is correct, a plot of k_{obs} against $[CrN^-]$ should give a straight line from which k_2 can be obtained. This was indeed found to be the case and the rate constant k_2 was obtained from the slope and found to be 8.44 l $mol^{-1} s^{-1}$ and

$t_{\frac{1}{2}} = 0.05$ s

The effect of temperature

In this experiment the reaction between the varying total concentrations of creatinine with total concentration of sodium hydroxide remaining constant against sodium nitroprusside was repeated at various temperatures from 25°C to 45°C. The kinetic data are presented in Tables 12, 13, 14, 15 and 16. The kinetic data when plotted against equilibrium concentration of creatinine carbanions give a linear graph.

Likewise, the reaction between the varying total concentration of sodium hydroxide with total concentration of creatinine remaining constant against sodium nitroprusside was repeated at various temperatures from 25°C to 45°C. The kinetic data are presented in Tables 10, 11, 12, 13, and 14.

Effect of Temperature

TABLE 12

Data for the reaction creatinine carbanion and sodium nitroprusside at 25°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.05	0.10	0.013	0.188
0.10	0.10	0.023	0.264
0.20	0.10	0.039	0.400
0.30	0.10	0.050	0.605
0.40	0.10	0.058	0.620

TABLE 13

Data for the reaction of creatinine carbanion and sodium nitroprusside at 30°C

$[\mathrm{CrNH}]_t$/M	$[\mathrm{OH}^-]_t$/M	$[\mathrm{CrN}^-]_e$/M	k_{obs}/s^{-1}
0.05	0.10	0.013	0.210
0.10	0.10	0.023	0.297
0.20	0.10	0.039	0.549
0.30	0.10	0.050	0.770
0.40	0.10	0.058	0.894

TABLE 14

Data for the reaction of creatinine carbanion and sodium nitroprusside at 35°C

$[\mathrm{CrNH}]_t$/M	$[\mathrm{OH}^-]_t$/M	$[\mathrm{CrN}^-]_e$/M	k_{obs}/s^{-1}
0.05	0.10	0.013	0.252
0.10	0.10	0.023	0.375
0.20	0.10	0.039	0.571
0.30	0.10	0.056	1.010
0.40	0.10	0.058	1.029

TABLE 15

Data for the reaction of creatinine carbanion and sodium nitroprusside at 40°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.05	0.10	0.013	0.263
0.10	0.10	0.023	0.444
0.30	0.10	0.039	0.612
0.30	0.10	0.050	1.170
0.40	0.10	0.058	1.380

TABLE 16

Data for the reaction of creatinine carbanion and sodium nitroprusside at 45°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.05	0.10	0.013	0.94
0.10	0.10	0.023	0.458
0.20	0.10	0.039	0.751
0.30	0.10	0.050	1.20
0.40	0.10	0.058	1.517

TABLE 17

Data for the reaction of equilibrium concentration of hydroxide and sodium nitroprusside at 25°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.10	0.05	0.013	0.13
0.10	0.10	0.023	0.35
0.10	0.20	0.039	0.60
0.10	0.30	0.050	0.84
0.10	0.40	0.058	1.30

TABLE 18

Data for the reaction of equilibrium concentration of sodium hydroxide and sodium nitroprusside at 30°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.10	0.05	0.013	0.17
0.10	0.10	0.023	0.40
0.10	0.20	0.039	0.73
0.10	0.30	0.050	1.03
0.10	0.40	0.058	1.69

TABLE 19

Data for the reaction of equilibrium concentration of sodium hydroxide and sodium nitroprusside at 35°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.10	0.05	0.013	0.21
0.10	0.10	0.023	0.47
0.10	0.20	0.039	0.74
0.10	0.30	0.050	1.03
0.10	0.40	0.058	1.89

TABLE 20

Data for the reaction of equilibrium concentration of sodium hydroxide and sodium nitroprusside at 40°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.10	0.05	0.013	0.26
0.10	0.10	0.023	0.49
0.10	0.20	0.039	0.88
0.10	0.30	0.050	1.19
0.10	0.40	0.058	2.09

TABLE 21

Data for the reaction of equilibrium concentration of sodium hydroxide and sodium nitroprusside at 45°C

$[CrNH]_t/M$	$[OH^-]_t/M$	$[CrN^-]_e/M$	k_{obs}/s^{-1}
0.10	0.05	0.013	0.28
0.10	0.10	0.023	0.62
0.10	0.20	0.039	0.93
0.10	0.30	0.050	1.49
0.10	0.40	0.058	2.16

The k_2 values from each slope of variation in the concentration of [CrNH] are shown in Table 22. An Arrhenius plot of lnk against $^1/T$ was done as shown in Table 23, and graph 6 from which the energy of activation was found to be 36.6 kJ mol^{-1}.

TABLE 22

Data for the rate constant at different temperatures for the reaction of creatinine carbanion and sodium nitroprusside

Temperature	k_2 l mol^{-1} s^{-1}
20°C	8.44
25°C	11.2
30°C	15.9
35°C	17.9
40°C	22.1
45°C	25.0

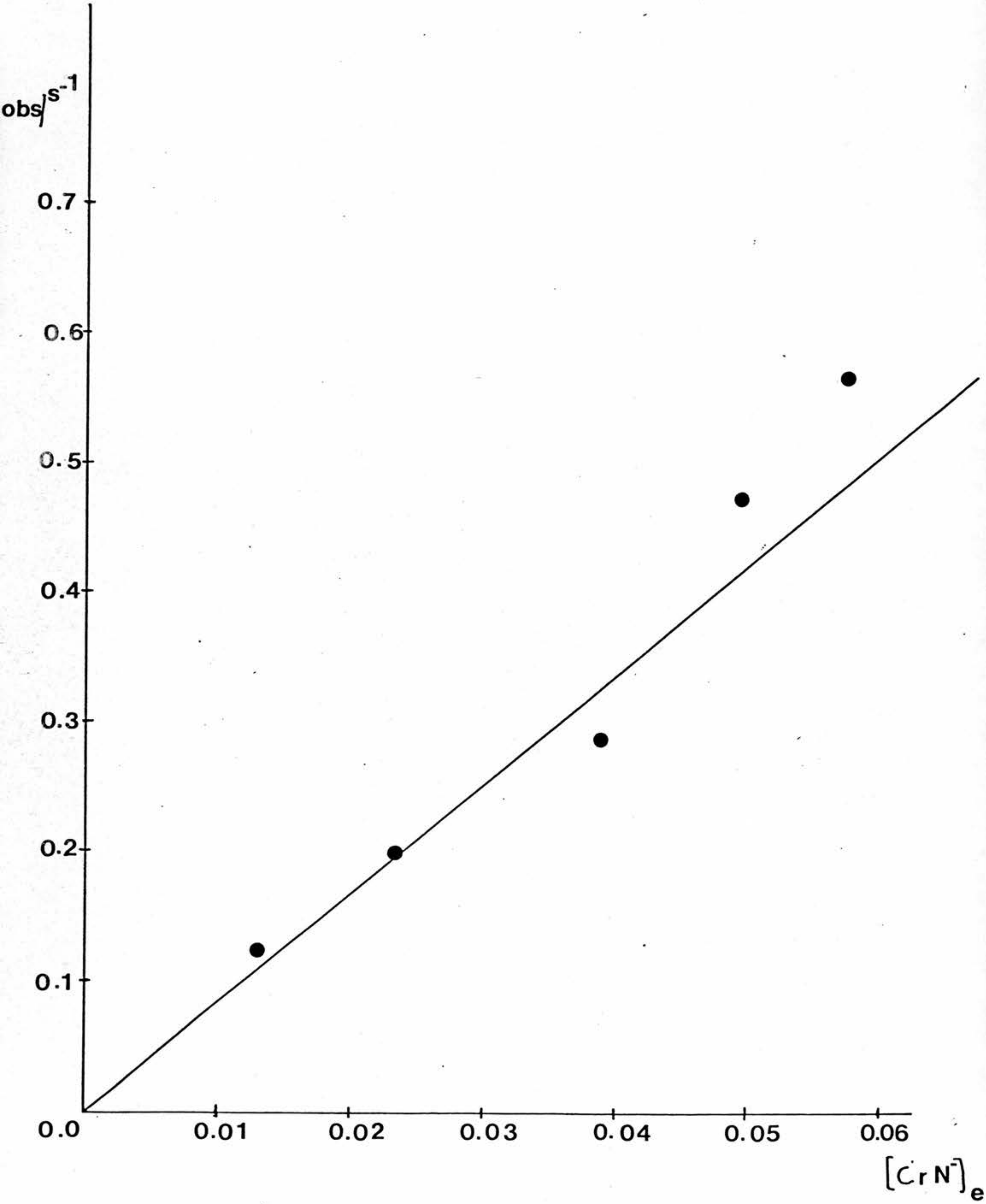
TABLE 23

Data for plot of lnk against $^1/T$

k_{obs}/s^{-1}	lnk	$T/^oC$	T/ K	T^{-1}/K^{-1}
8.44	2.1329	20	293	0.003413
11.24	2.4194	25	298	0.003356
15.91	2.7669	30	303	0.003300
17.86	2.8825	35	308	0.003247
22.12	3.0964	40	313	0.003195
25.0	3.2188	45	318	0.003145

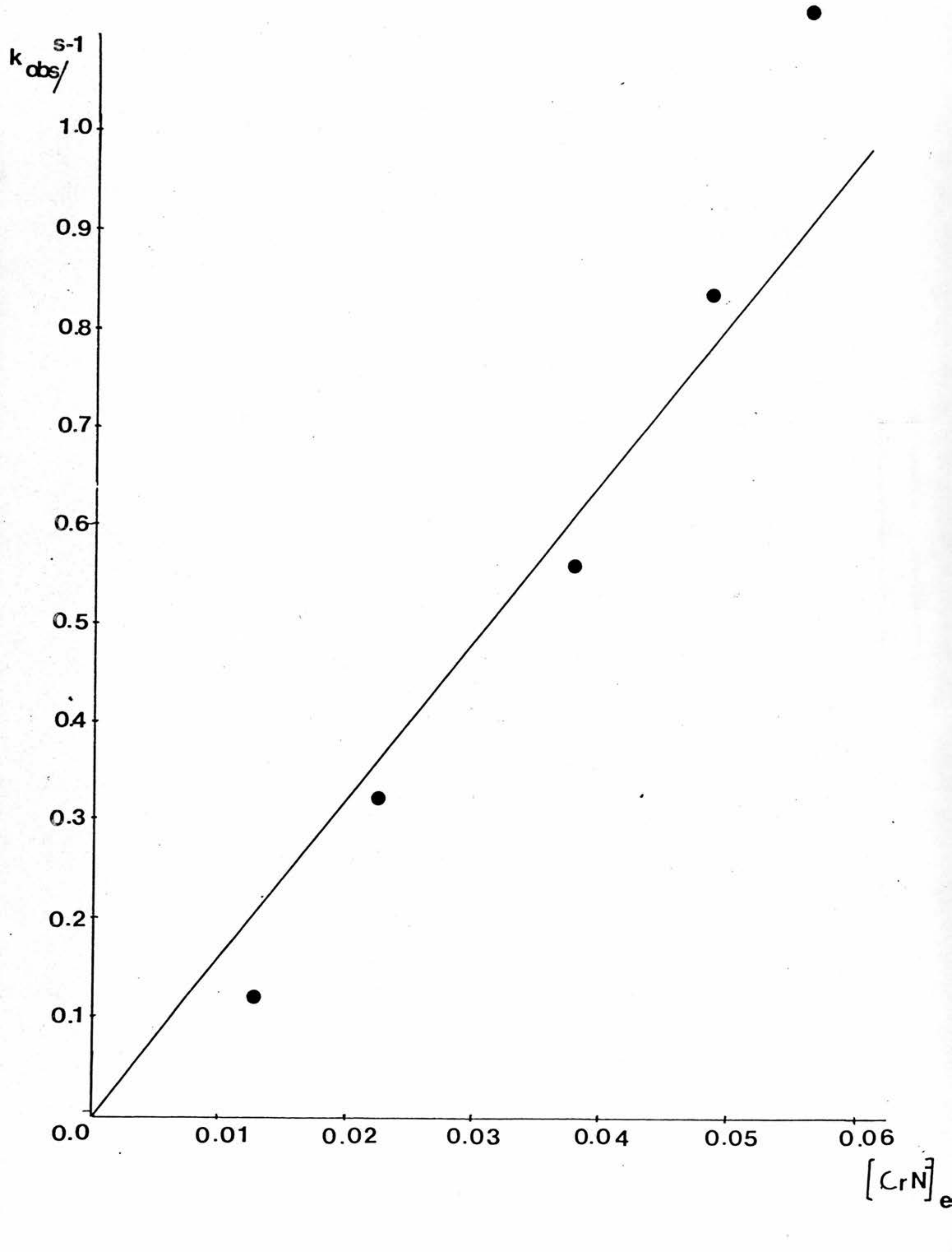
Graph 4

A plot of k_{obs} against equilibrium concentration of creatinine carbanion with varying in the concentration of (CrNH) at 20°C



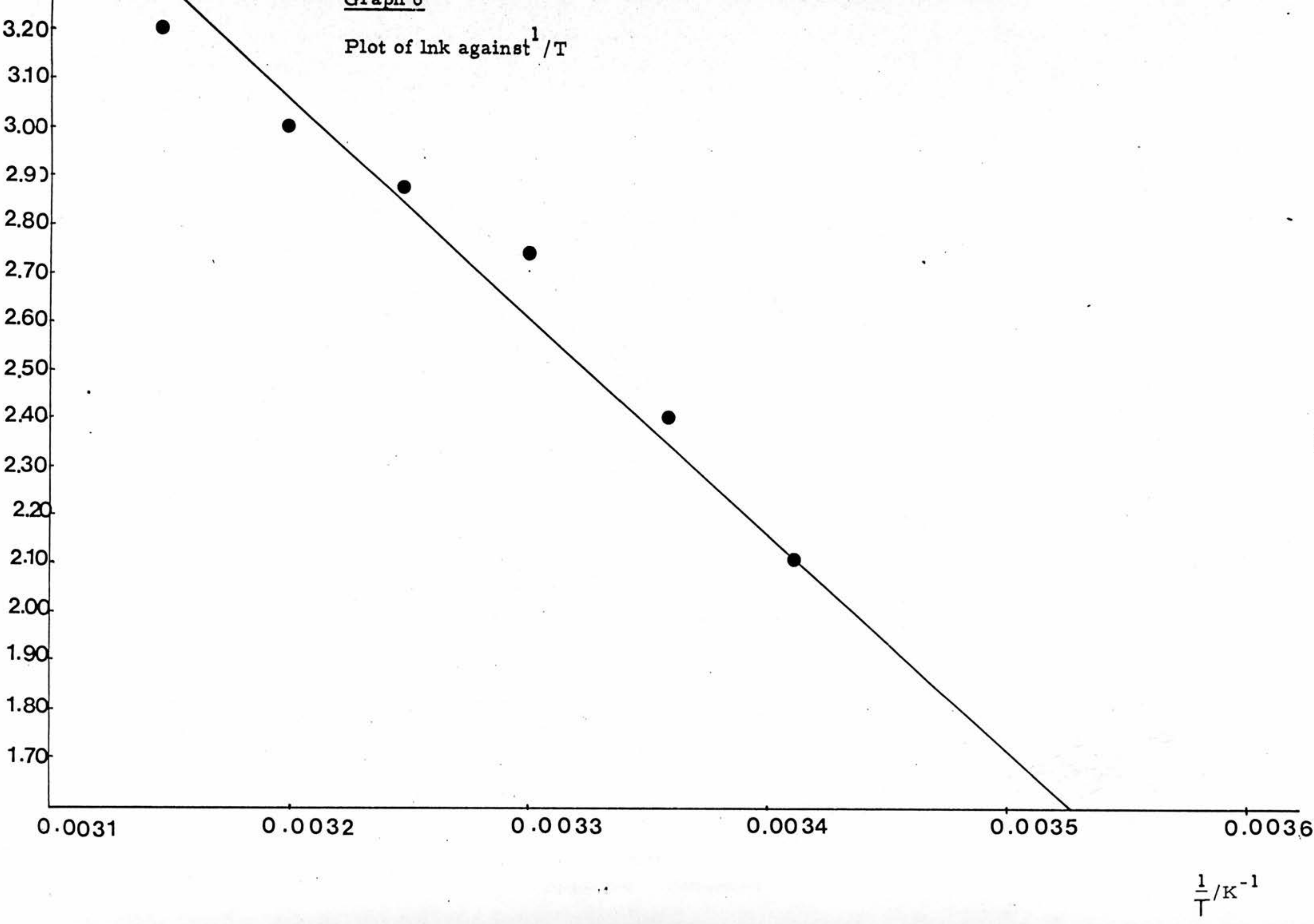
Graph 5

The plot of k_{obs} against equilibrium concentration of creatinine carbanions with varying in the concentration of (NaOH) at 20°C



Graph

Plot of lnk against $^{1}/T$



SUMMARY AND CONCLUSION

The work reported in chapter 2 between sodium nitroprusside and creatinine in the presence of sodium hydroxide can be summarised as follows :-

(i) It was found, firstly, that a plot of k_{obs} against equilibrium concentration of creatinine carbanion with varying in the concentration of creatinine and secondly, a plot of k_{obs} against equilibrium concentration of creatinine carbanions with varying in the concentration of hydroxide showed that both graphs are linear. This suggests that it is a first order in creatinine carbanion and also first order in nitroprusside anions. The dependence of k_{obs} on $[CrNH]_t$ is because creatinine is a weak acid hence k_{obs} appears to be proportional to $[CrNH]_t$ and $[OH^-]_t$.

(ii) The creatinine carbanion will react with sodium nitroprusside to give a red coloration and it is this which is the rate-determining step (k_2).

(iii) It was also found that the plot of k_{obs} against creatinine equilibrium concentration was linear at some temperatures. The k_2 values from each slope were obtained. An Arrhenius plot of lnk against $^1/T$ was drawn from which the energy of activation was calculated.

CHAPTER 3

Kinetic studies of the reaction between malononitrile and sodium nitroprusside.

INTRODUCTION

The reaction of sodium nitroprusside with malononitrile in the in the presence of sodium hydroxide is another example of a carbanion reaction, as again the colour is developed only the presence of alkali. The intense red colour fades to staw yellow. This is known as the Legal[81] reaction. The study of the investigation was carried out on the stopped-flow spectrophotometer using similar procedures to that previously described. The optical density was measured at 510 nm as a function of time. The stopped-flow spectrophotometer was connected via a transcient recorder to a microcomputer which allowed immediate calculation of the rate constants.

The observed kinetics in this case proved much more difficult to interpret in mechanistic terms than was the case for creatinine.

PROCEDURE

This experiment was studied on the stopped-flow spectrophotometer using a wavelength of 510 nm. A solution of sodium nitroprusside and malononitrile was placed in one arm of the stopped-flow spectrophotometer, while the other contained sodium hydroxide. In another series of experiments malononitrile and sodium hydroxide were placed in one arm and sodium nitroprusside in the other. The values of k_{obs} obtained were unchanged, indicating that the proton removal from the malononitrile is not the rate-determining step. The former method was preferred as a mixture of malononitrile and sodium hydroxide was found to be unstable over a few hours.

In the first series of experiments the reaction at 25°C was investigated. The concentration of sodium nitroprusside was made up to 0.001M and the concentrations of malononitrile and hydroxide were made ten times greater. In the first series of reactions the concentration of malononitrile was varied. The values of k_{obs} obtained are displayed in Table 24. Correlation coefficients were always better than 0.990.

The half-life of this reaction under these conditions is found to be constant at ca 100 ms. The significant matter is that the value of k_{obs} varied only slightly, although the concentration of the malononitrile was changed by a factor of five.

The effect of ionic strength on the rate

The effect of changing the ionic strength upon the rate of reaction was examined by adding potassium chloride. The results are shown in Table 25.

It is clear that changing the ionic strength does have a slight effect upon the rate constant. However, this is small enough to be neglected as this is only a preliminary investigation of the reaction.

Table 26 gives the result of the varying hydroxide concentration at constant malononitrile concentrations.

TABLE 24

Variation of k_{obs} with malononitrile concentration

[SNP] = 0.0010 M

$[CH_2(CN)_2]_t^*$/M	$[NaOH]_t^*$/M	k_{obs}/s^{-1}
0.010	0.050	6.95
0.020	0.050	9.60
0.030	0.050	10.48
0.040	0.050	8.99
0.050	0.050	8.26

* The term $[CH_2(CN)_2]_t$ is the total concentration of malononitrile added and $[NaOH]_t$ is the total concentration of hydroxide added.

TABLE 25

Effect of potassium chloride concentration on the value of k_{obs}

[SNP] = 0.0010 M

Reactants	[KCl]/M	k_{obs}/s^{-1}
$[CH_2(CN)_2]$ 0.03 M [NaOH] 0.05	0.01	3.76
$[CH_2(CN)_2]$ 0.03 M [NaOH] 0.05 M	0.03	4.92
$[CH_2(CN)_2]$ 0.03 M [NaOH] 0.05 M	0.05	5.62

TABLE 26

Variation of k_{obs} with sodium hydroxide concentration

[SNP] = 0.0010 M

$[NaOH]_t$/M	$[(CH(CN)_2]_t$/M	k_{obs}/s^{-1}
0.010	0.050	0.23
0.020	0.050	0.86
0.030	0.050	2.60
0.040	0.050	6.01
0.050	0.050	13.0

The values of k_{obs} for the reaction increased very rapidly as the concentration of sodium hydroxide was increased. I concluded that the role of sodium hydroxide in determining the rate of reaction was more than formation of the malononitrile carbanion.

In the previous series of experiments sodium hydroxide concentration was constant and the malononitrile concentration was varied. The result obtained was a completely different dependence of k_{obs} upon the concentration of variable reactant. This is shown in Table 24.

The interpretation of these kinetic results in terms of a mechanism proved difficult. Obviously the concentration of malononitrile carbanion is a crucial factor and this is calculated in all cases by applying the following quadratic equation.

<u>Calculation for $[CH(CN)_2]$</u>

MH = Malononitrile

M^- = Malononitrile carbanion

$$MH + OH^- \rightleftharpoons M^- + H_2O$$

$$[M^-] = \frac{K_a}{K_w} \quad ([MH]_t - [M^-])([OH^-]_t - [M^-])$$

This is a quadratic in $[M^-]$

$K_a = 6.46 \times 10^{-12}$ (see reference 82)

$K_w = 1.007 \times 10^{-14}$

$$\frac{K_a}{K_w} = \frac{6.46 \times 10^{-12}}{1.007 \times 10^{-14}} = 6.45 \times 10^{2}$$

Example calculation

$[CH_2(CN)_2]_t$ = 0.05 M $[NaOH]_t$ = 0.01 M

$$[M^-] = 645.7\ (0.05 - [M^-])\ (0.01 - [M^-])$$

$$[M^-] = 0.3229 - 39.7\ M + 645.7\ [M^-]^2$$

$$[M^-] = 0.3229 - 39.7\ M + 645.7 + M^-]^2$$

$$[M^-] = \frac{39.7 \pm \sqrt{1576 - 834}}{1291}$$

$$[M^-] = \frac{39.7 \pm 27.9}{1291}$$

$$[M^-] = 0.00914\ M$$

The following results are obtained for the equilibrium of malononitrile carbanions per Table 27.

TABLE 27

Concentration of malononitrile carbanion

$[CH_2(CN)_2]_t$/M	$[NaOH]_t$/M	$[\bar{C}H(CN)_2]_e^*$/M
0.01	0.05	0.00914
0.02	0.05	0.0191
0.03	0.05	0.0275
0.04	0.05	0.0354
0.05	0.05	0.0420

* $[\bar{C}H(CN)_2]_e$ is the equilibrium concentration of carbanion and $[OH^-]_e$ is the equilibrium concentration of the hydroxide.

The values for $[OH^-]_e$ are obtained by subtracting $[\bar{C}H(CN)_2]_e$ from $[NaOH]_t$ (see Table 28).

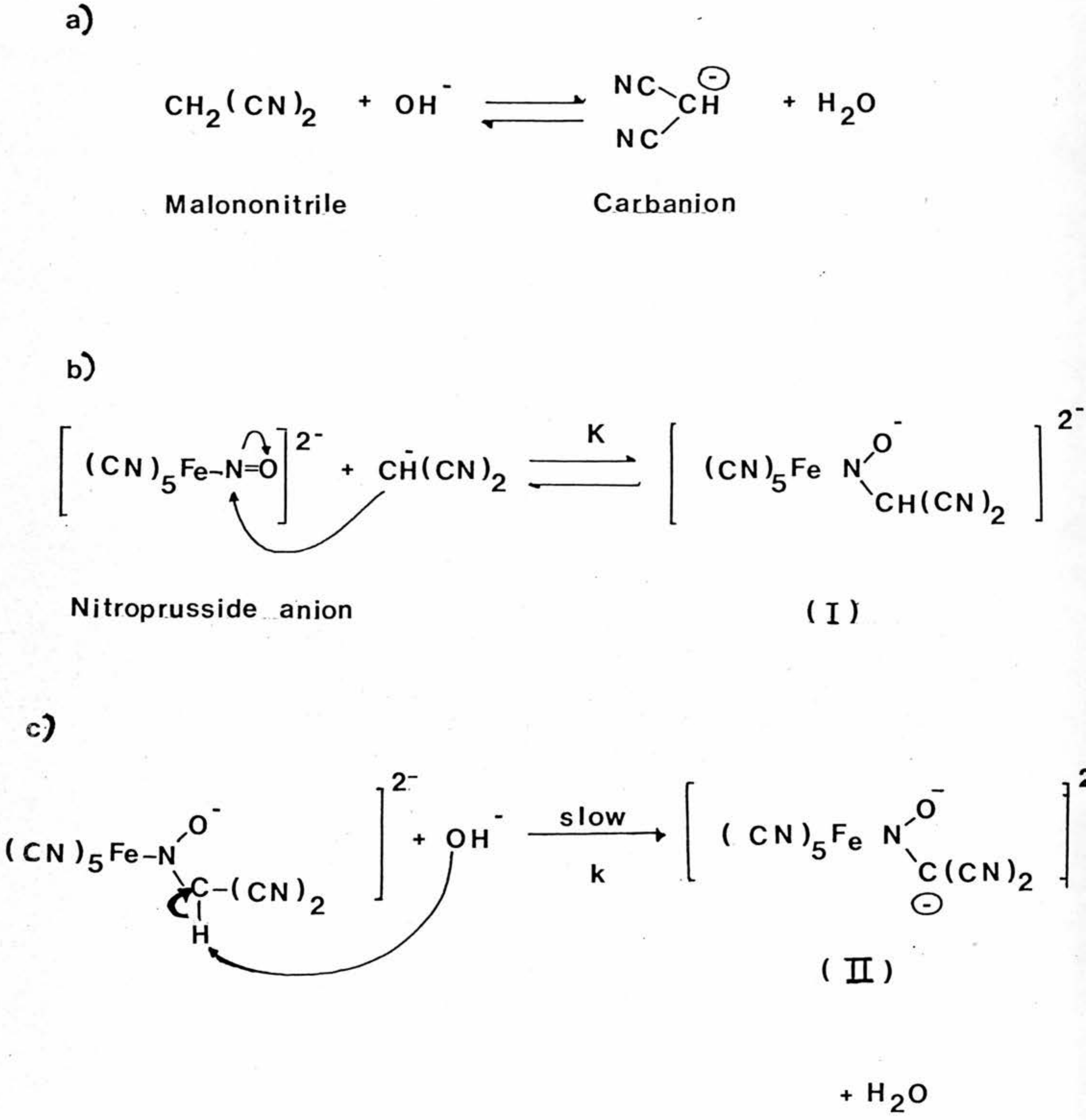
The obvious and expected result was that k_{obs} would be directly proportional to the malononitrile carbanion concentration. Inspection of the data in Table 28 show that this is not the case. I sought, therefore, another mechanism which was consistent with these results.

TABLE 28

Variation of k_{obs} with malononitrile carbanion concentration

$[CH_2(CN)_2]_t$/M	$[NaOH]_t$/M	$[\overline{C}H(CN)_2]_e$/M	$[NaOH]_e$/M	k_{obs}/s^{-1}
0. 010	0. 050	0. 00914	0. 0409	6. 592
0. 020	0. 050	0. 0191	0. 0309	9. 600
0. 030	0. 050	0. 0275	0. 0225	10. 476
0. 040	0. 050	0. 0359	0. 0141	8. 994
0. 050	0. 050	0. 0420	0. 0080	8. 260

It would seem that the values of k_{obs} depend not only on the concentration of the malononitrile carbaions but also upon the concentration of the sodium hydroxide ion at equilibrium. Some of the hydroxide ions are neutralised by the malononitrile in forming the carbanions.


a)
CH2(CN)2 + OH- ⇌ NC, NC, CH (carbanion) + H2O
Malononitrile
Carbanion
b)
[(CN)5Fe-N=O]2- + CH(CN)2
K
[(CN)5Fe N O- CH(CN)2]2-
Nitroprusside anion
(I)
c)
(CN)5Fe-N O- C-(CN)2 H
2-
+ OH-
slow
k
[(CN)5Fe N O- C(CN)2]
(II)
+ H2O

Scheme 3

The only reaction scheme consistent with the kinetic data which have been given so far is shown in Scheme 3.

Explanation of Scheme 3

Two equilibria are involved in the formation of the red compound in the reaction between nitroprusside and malononitrile carbanion. The postulated mechanism is shown in Scheme I where (II) is bright red. The equation (a) shows the equilibrium between the malononitrile and hydroxide to form a carbanion. All the calculations following are based upon the equilibrium concentration of both hydroxide and malononitrile. Equation (b) represents the equilibrium which leads to the formation of the complex (I) formed by the addition of the malononitrile carbanion to the nitrosyl of the nitroprusside ion. Equation (c) represents the slow removal of a proton from species (I) by OH^- to form the red species (II) which has an overall negative charge of four. This is the species whose appearance is being followed. This is the rate determining step.

The algebra for this reaction scheme is as follows :-

$$[I] = K[NP^{-2}]\,[\bar{C}H(CN)_2]_e$$

$$\frac{d(II)}{dt} = k[I]\,[^-OH]_e$$

$$= Kk[NP^{-2}]\,[CH^-(CN)_2]_e[OH^-]_e$$

assuming that the value of K is small.

$$k_{obs} = Kk\,[\bar{C}H(CN)_2]_e[OH^-]_e$$

From this it can be seen that, a plot of k_{obs} divided by the equilibrium concentration of hydroxide against malononitrile carbanion should give a straight line. The slope in this case will be the product of equilibrium constant K and the rate constant k. A straight line is obtained. Graphs 7 and 8 pages 91 and 93 show that the data in Tables 29 and 30 are consistent with the proposed mechanism.

There is no independent evidence for this reaction scheme. The kinetics were repeated many times and always gave consistent results, and the proposed reaction mechanism is the only one which fits the data.

TABLE 29

In which malononitrile concentration is varied at 25°C

$k_{obs}/_{[OH^-]}$ /$s^{-1}M^{-1}$	$[\bar{C}H(CN)_2]_e$/M
1.62	0.92
3.11	1.91
4.66	2.73
6.38	5.59
10.33	4.20

Graph 7

Reaction of SNP with malononitrile carbanion at 25°C

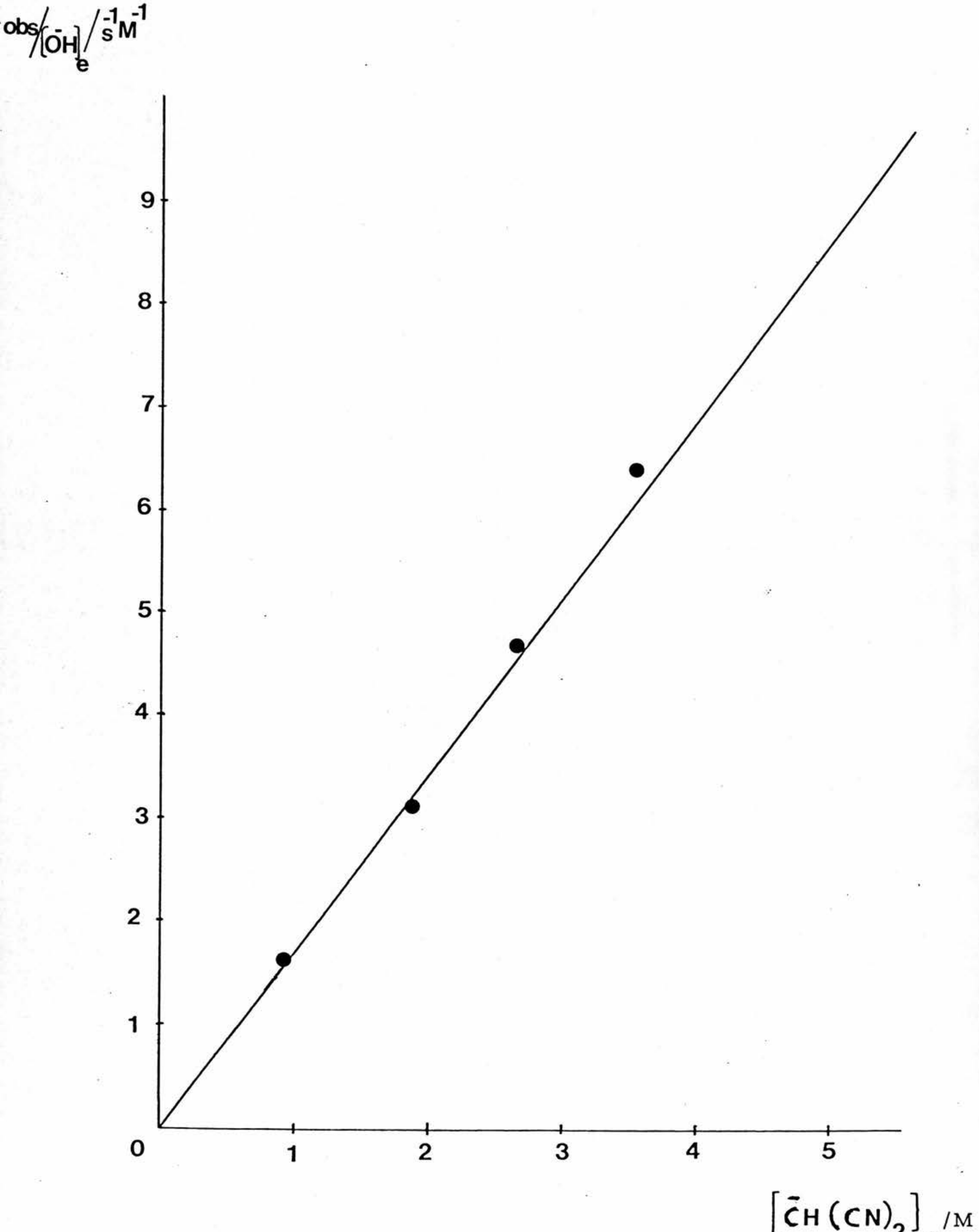


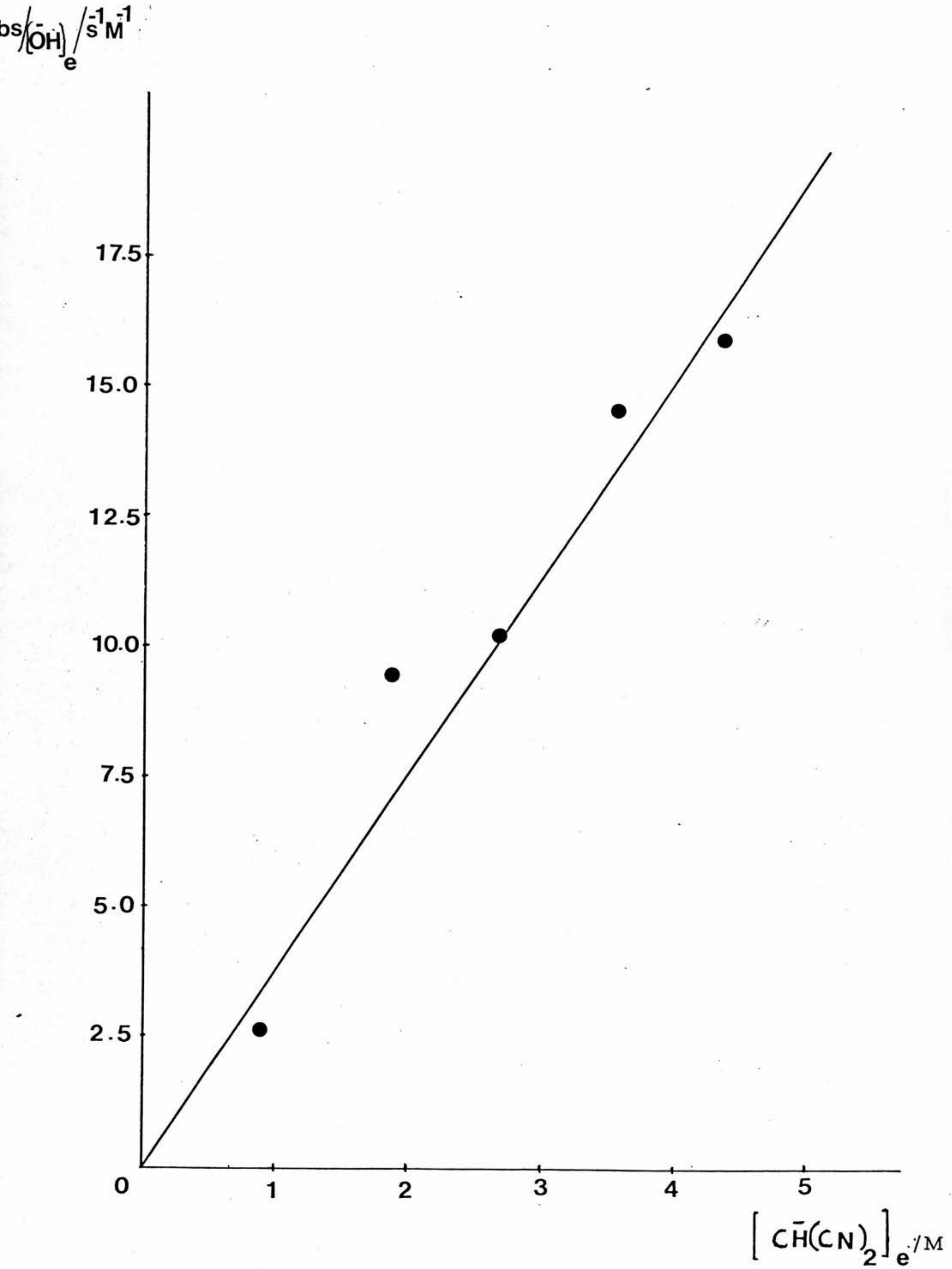
TABLE 30

Data in which sodium hydroxide concentration is varied at 25°C

$k_{obs}/[\bar{O}H]$ /$s^{-1}M^{-1}$	$[CH^{-}(CN)_2]_e$/M
2.68	0.92
9.56	1.91
10.4	2.75
14.69	3.60
16.25	4.20

Graph 8

Reaction of SNP with malononitrile carbanion at 25°C



Effect of temperature

The effect of temperature on the value of k_{obs} was determined and the results are given below in Tables 31, 32, 33, 34 and 35.

TABLE 31

Data for the reaction of malononitrile carbanion and sodium nitroprusside at 20°C

$[CH_2(CN)_2]_t/M$	$[NaOH]_t/M$	k_{obs}/s^{-1}
0.01	0.05	7.25
0.02	0.05	10.20
0.03	0.05	11.33
0.04	0.05	10.53
0.05	0.05	7.64

TABLE 32

Data for the reaction of malononitrile carbanion and sodium nitroprusside at 30°C

$[CH_2(CN)_2]_t$/M	$[NaOH]_t$/M	k_{obs}/s^{-1}
0.01	0.05	6.35
0.02	0.05	9.57
0.03	0.05	10.28
0.04	0.05	8.93
0.05	0.05	7.97

TABLE 33

Data for the reaction of malononitrile carbanion and sodium nitroprusside at 35°C

$[CH_2(CN)_2]_t$/M	$[NaOH]_t$/M	k_{obs}/s^{-1}
0.01	0.05	5.70
0.02	0.05	8.72
0.03	0.05	9.12
0.04	0.05	7.24
0.05	0.05	6.80

TABLE 34

Data for the reaction of malononitrile carbanion and sodium nitroprusside at 40°C

$[CH_2(CN)_2]_t$/M	$[NaOH]_t$/M	k_{obs}/s^{-1}
0.01	0.05	5.56
0.02	0.05	8.34
0.03	0.05	9.45
0.04	0.05	6.63
0.05	0.05	6.36

TABLE 35

Data for the reaction of malononitrile carbanion and sodium nitroprusside at 45°C

$[CH_2(CN)_2]_t$/M	$[NaOH]_t$/M	k_{obs}/s^{-1}
0.01	0.05	5.54
0.02	0.05	7.97
0.03	0.05	8.76
0.04	0.05	7.18
0.05	0.05	6.74

It is assumed that the equilibrium concentrations of malononitrile carbanion and hydroxide ions are unchanged by changing the temperature. This will probably introduce a small error but it is not significant in the analysis of these results.

The plot of k_{obs} divided by equilibrium of OH^- against malononitrile equilibrium concentrations is linear at all temperatures (see graphs 9, 10, 11, 12 and 13). The slope of this line is equal to Kk, i. e. the rate constant for the slow step and the equilibrium constant. It is observed that the value of Kk does not vary very much with temperature. It is almost certain that k will increase with temperature, i. e. the slow step will get faster as the temperature is increased. This increase must therefore be offset by a decrease in the value of K such that the products of the two is virtually independent of the temperature.

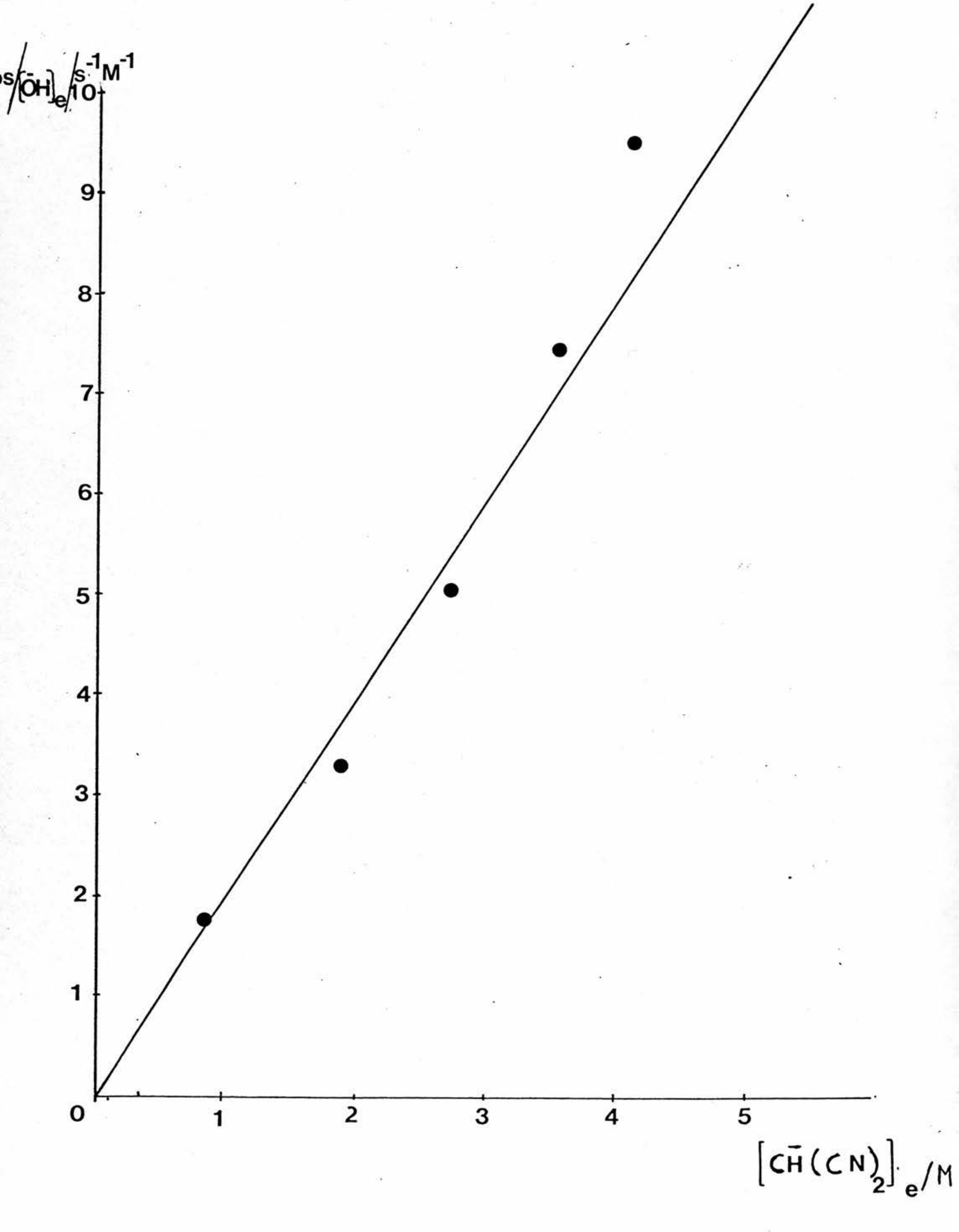
The last point on these graphs is considerably off. This is probably due to the error involved in subtracting $[\bar{C}H(CN)_2)_e$ from $[CH_2(CN)_2]_t$ becoming significant as the difference gets small.

The values of Kk for the various temperatures are shown in Table 36, page 103.

It is not possible from the data available to separate the product of Kk into the two individual components.

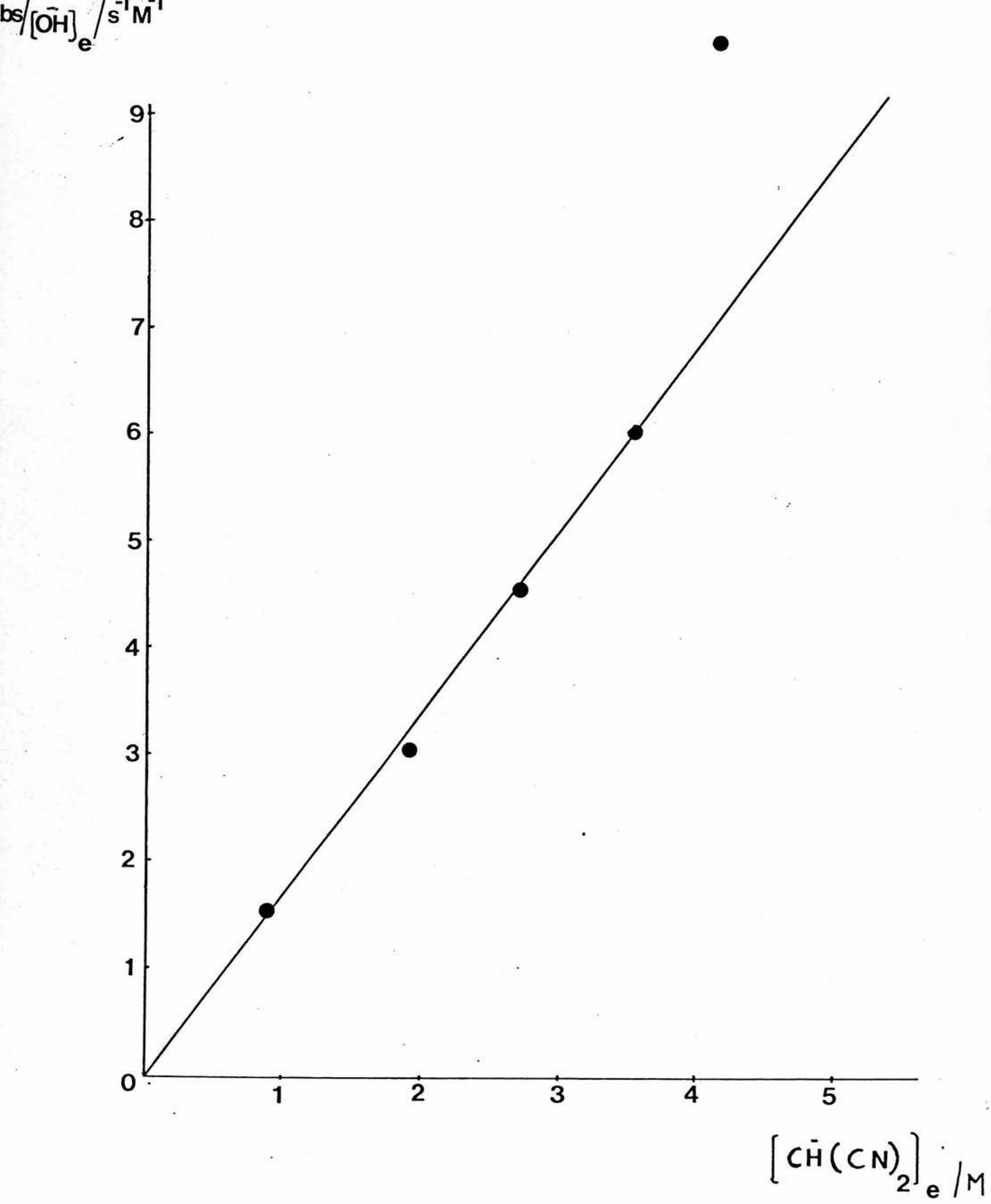
Graph 9

Reaction of SNP with malononitrile carbanion at 20°C



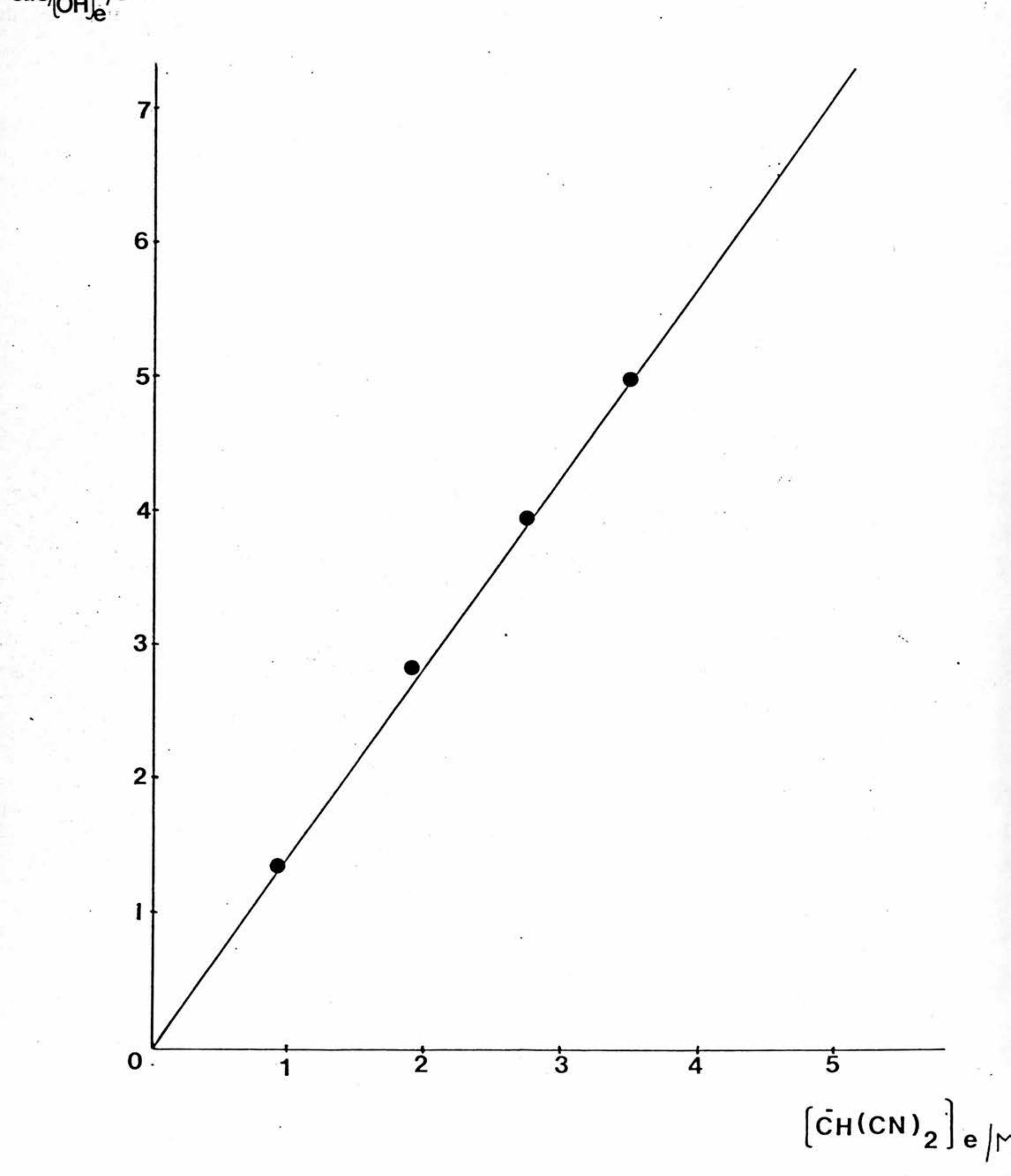
Graph 10

Reaction of SNP with malononitrile carbanion at 30°C



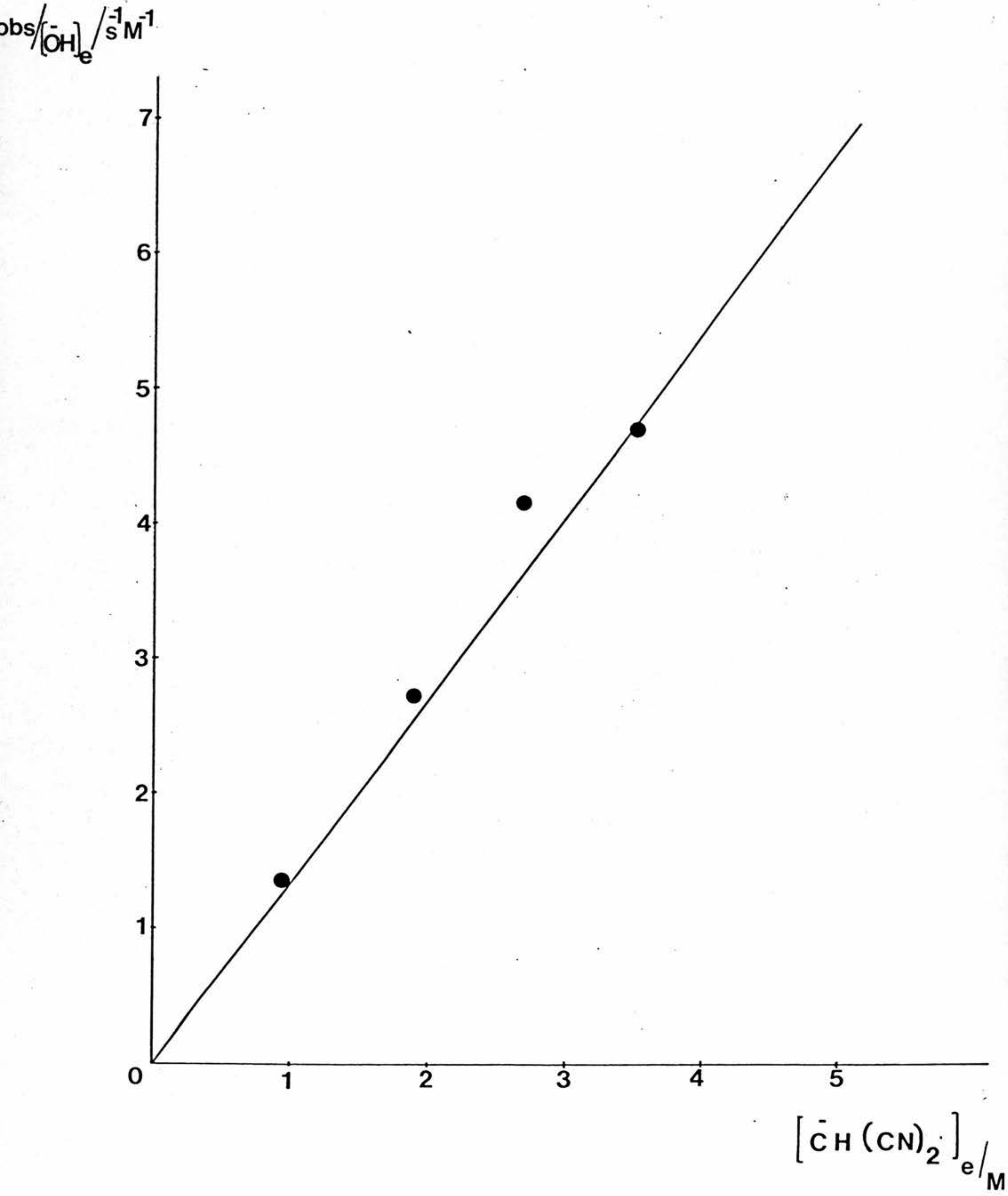
Graph11

Reaction of SNP with malononitrile carbanion at 35^{o}C



Graph 12

Reaction of SNP with malononitrile carbanion at 40°C



Graph 13

Reactions of SNP with malononitrile carbanions at 45°C

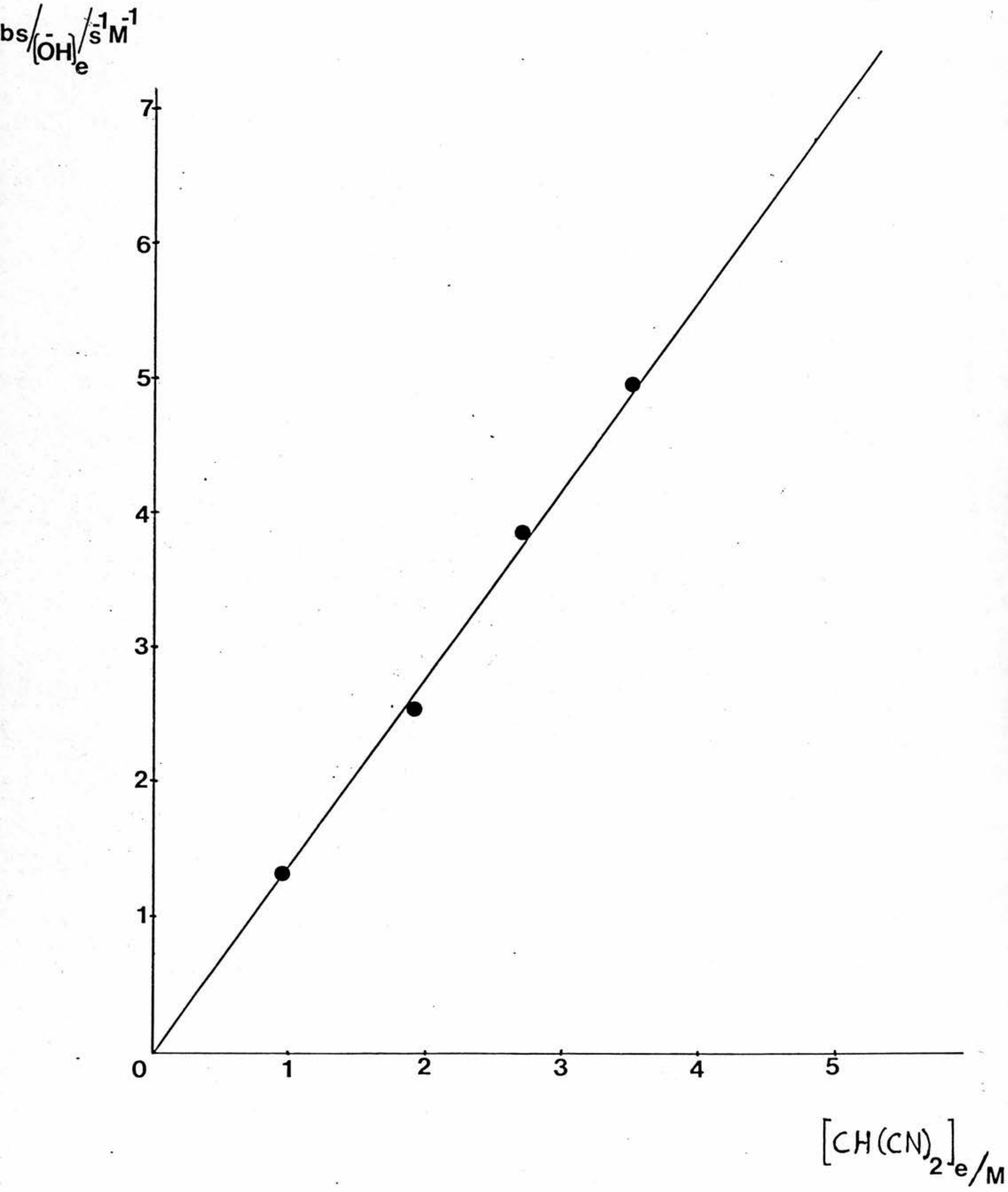


TABLE 36

The values of Kk calculated from the slope of Graphs 9, 10, 11, 12 and 13

Temperature of water bath	Kk / $M^{-2}s^{-1}$
20°C	1.96
25°C	1.70
30°C	1.68
35°C	1.43
40°C	1.34
45°C	1.40

The formation of the straw colour solution from bright red solution

The purple-red solution which I believe is due to the species (II) is not stable but fades within minutes. However, it is fortunate that the rates for these two processes are significantly different that the kinetic investigation for the formation could be examined, and likewise the kinetic of its disappearance.

The rate of the disappearance is outside the range of the stopped-flow spectrophotometer. However, further investigation into the rate constants for the disappearance is measured on a more conventional spectrophotometer, i.e. SP8100. The results are given in Table 37.

TABLE 37

Data for the disappearance of red colour at 25°C

SP 8100

Wavelength 510 nm

[NaOH]/M	$[CH_2(CN)_2]_t$ = 0.05 M [SNP] = 0.01 M	k_{obs}/s^{-1}
0.01	0.05M + 0.01M	0.0202
0.02	0.05M + 0.01M	0.0204
0.03	0.05M + 0.01M	0.0304
0.04	0.05M + 0.01M	0.0200
0.05	0.05M + 0.01M	0.0204
0.06	0.05M + 0.01M	0.0212
0.07	0.05M + 0.01M	0.0214
0.08	0.05M + 0.01M	0.0209
0.09	0.05M + 0.01M	0.0194
0.10	0.05M + 0.01M	0.0187

Clearly the values of k_{obs} does not vary with the concentration of the reactants and this is the conclusion predicted earlier on the stopped-flow spectrophotometer. The reaction is pseudo first order in species (II) and did not depend on any other species present in the reaction mechanism. The fact that the rate is independent of the concentrations of other reactants suggest that the rate determining step of the fading reaction is the unimolecular breakdown of the red species (II).

This observation is similar to that drawn by Swinehart for the reaction of carbanion derived from ketones and sodium nitroprusside.

Isolation and identification of the red intermediate and the organic compound

Method

A mixture of malononitrile (5g) and sodium hydroxide (5g) was dissolved in the minimum amount of distilled water. To this was added sodium nitroprusside (5g) dissolved in distilled water. This gave an immediate red colour. On addition of 20ml acetonitrile the red product was precipitated. The product was washed and recrystallised from methanol and identified by mass spectra, microanalysis and atomic absorption.

The final straw yellow product resulting from the fading of the red intermediate was harder to isolate from acetonitrile. This was partly because of the inherent instability of this compound and also partly because of experimental difficulties.

The organic product of the reaction was prepared by the same procedure. The red aqueous solution was allowed to fade, then extracted with methylene chloride. Evaporation of the solvent gave the product.

Identification

The investigation of the mass spectra of the red intermediate compound gives no clear significant data. The application of microanalysis and atomic absorption carried out on an isolated sample of this intermediate gave the following results :

Microanalysis	Carbon	Hydrogen	Nitrogen
	21.35%	1.55%	25.05%

This gives the indication that the intermediate has 1:1 C to N ratio probably contains CN group.

Atomic Absorption

The result obtained from the calibration curve showed sodium to be present as 40.2 ppm, i.e. 20.2% and that of iron 25.8 ppm, i.e. 13.37%.

This gives a Na to Fe ratio of 3.9:1 and the varification that the intermediate may have formula

$$[Na_3(CN)_5FeN(O)C(CN)_2]^-Na^+.XH_2O$$

Microanalysis results are not highly accurate, but they suggest that x = 4, i.e. that the intermediate is $[Na_3(CN)_5FeN(O)C(CN)_2]^-Na^+3H_2O$

Investigation into the analysis of the organic product resulting from the fading of the red colour to the straw colour was carried out by microanalysis and infrared spectrum.

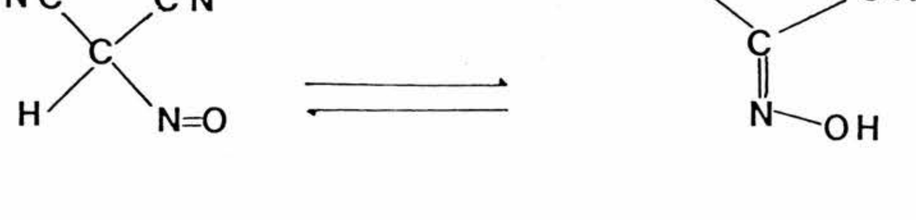
The results of the infrared show the appearance of the following bands :

Found	-OH	-C=N	-N=0	-R-NO
IR band wave number cm^{-1}	3500-3700	2200-2300	-1600	-1400

The microanalysis shows the following results :

Expected analysis of the organic compound	C = 44.20%	H = 1.06%	N = 37.9%
Found analysis of the organic compound	C = 43.98%	H = 1.53%	N = 37.1%

The results of the analysis of the organic product of the reaction showed that the formula is $(CN)_3OH$. Furthermore, the compound can be shown to exist in two tautomeric forms which are consistent with the observed infrared.

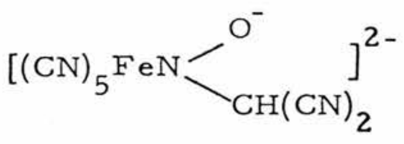


SUMMARY AND CONCLUSION

The conclusion drawn from the evidence collected for the reaction between sodium nitroprusside and malononitrile in the presence of sodium hydroxide is that the mechanism proposed in Scheme I is correct. This is supported by the kinetic data. The evidence can be summarised in the following ways :-

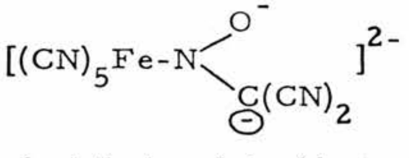
(1) It was found that the values of k_{obs} was unchanged when a mixture of sodium nitroprusside and malononitrile was allowed to react with sodium hydroxide and when a mixture of malononitrile and sodium hydroxide was allowed to react with sodium nitroprusside. This gives the indication that the proton removal from the malononitrile is not the rate-determining step.

(2) The rate-determining step in this reaction is the slow removal of a proton from species (I)



$$[(CN)_5FeN(O^-)CH(CN)_2]^{2-}$$

by OH^- to form the red species (II)



$$[(CN)_5Fe\text{-}N(O^-)\underset{\ominus}{C}(CN)_2]^{2-}$$

This is shown by the fact that a plot of k_{obs} divided by the equilibrium concentration of hydroxide against malononitrile carbanion gave a straight line, the slope being the product of equilibrium constant K and the rate constant k.

(3) The identities of the red intermediate and the organic product of the reaction were consistent with the proposed mechanism.

(4) It was also found that the plot of k_{obs} divided by the equilibrium

of OH^- against malononitrile equilibrium concentration was linear at all temperatures and the values of Kk did not show much change.

(5) The fading reaction of the intermediate (II) was found to be independent of the concentration of any other species present in the reaction mechanism and concluded that it is the unimolecular breakdown of species (II).

APPENDIX

Kezdy-Swinbourne[83,84,85] method for the determination of a first-order rate constant (k)

Consider a first-order reaction of which observations ($x_o, x_1, x_2, \ldots\ldots x_n \ldots\ldots x_\infty$) are made at times o $t_1, t_2 \ldots\ldots t_n \ldots \infty$.

For a reading (x_n) taken at t_n

$$(x_\infty - x_n) = (x_\infty - x_o)\exp(-kt_n) \qquad (1)$$

For a reading (x'_n) taken Δt seconds later

$$(x_\infty - x'_n) = (x_\infty - x_o)\exp[-k(t_n + \Delta t)] \qquad (2)$$

Divide (1) by (2)

$$(x_\infty - x_n)\exp(kt_n) = (x_\infty - x'_n)\exp[k(t_n + \Delta t)]$$

$$x_n = x_\infty[1 - \exp(k\Delta t)] + x'_n \exp(k\Delta t)$$

$$Y = \qquad C \qquad + x \quad m$$

Plot x_n against x'_n with Δt constant (x_n along y axis and x'_n along the x axis)

$$\text{slope} = \exp(k\Delta t)$$

$$\ln(\text{slope}) = k\Delta t$$

$$k = \ln(\text{slope})/\Delta t$$

When $x_n = x'_n$, then the value of x is x_∞.

Make Δt = 0.5 to 1.0 of the reaction half-line.

REFERENCES

1. L. Playfair, Liebigs. Chem., 1850, 74, 317.
2. A. Overbeck, Anch. Pharm., 1853, 122, 270.
3. I. Kyd, Ann. Chem., 1850, 74, 340.
4. R. Wild, Anch. Pharm., 1855, 131, 26.
5. A. Schafarik, J. Prakt. Chem., 1863, 9a, 19.
6. F. Hyde, J. Amer. Chem. Soc., 1897, 19, 23.
7. E. Hadow, J. Amer. Chem. Soc., 1866, 2, 341.
8. G. Stadeler, Ann. Chem., 1869, 151, 8.
9. M. Prad Homme, Compt. Mend., 1890, 111, 45.
10. C. Deventer, Ber., 1893, 26, 589.
11. P. Schwarzkopf, Chem. Zentr., 1912, 11, 1536.
12. O. Baudisch, Ber., 1929, 62, 2700.
13. Yu. V. Karyakin and I. I. Angelov, "Chistye Khimiehiskie Reaktivy" (Pure Chemical Reagents), Goskhimizadat, Moscow, 1955, p. 391.
14. W. Weith, Ann. Chem., 1868, 147, 312.
15. E. Davy, J. Prakt. Chem., 1853, 59, 502.
16. H. Jensen, J. Pharm. Chem., 1853, 59, 502.
17. L. Potsdamer, J. Ind. Eng. Chem., 1919, 11, 769.
18. P. T. Manoharan and W. C. Hamilton, Inorg. Chem., 1963, 2, 1043.
19. G. Johansson and W. N. Lipscomb, Acta Cryst., 1958, 11, 594.

20. J. T. Thomas, J. H. Robertson and E. G. Fox, Acta Cryst., 1958, 11, 599.

21. W. P. Griffith, Quart. Revs., 1962, 16, 188.

22. F. A. Cotton, R. R. Monchamp, R. J. M. Henry and R. C. Young, J. Inorg. Nuclear Chem., 1959, 10, 28.

23. F. A. Miller and C. H. Wilkins, Anal. Chem., 1952, 24, 1253.

24. E. F. G. Herington and W. Kynaston, J. Chem. Soc., 1955, 3555.

25. J. Lewis, R. J. Irving and G. Wilkinson, J. Inorg. Nuclear Chem., 1958 7, 32.

26. G. Bor, J. Inorg. Nuclear Chem., 1961, 17, 174.

27. L. Tosi and J. Danon, Inorg. Chem., 1964, 3, 150.

28. B. Jezowska-Trzebiatowska and J. Ziolkowski, Bull. Acad. Polon. Sci. Ser. Sci. Chim., 1964, 12, 503.

29. W. Beck and H. S. Smedal, Z. Naturforsch., 1965, 206, 109.

30. E. L. Saier and A. Pozefska, Anal. Chem., 1954, 26, 1079.

31. D. J. Millen and D. Watson, J. Chem. Soc., 1957, 1369.

32. W. P. Griffith, J. Lewis and G. Wilkinson, J. Inorg. Nuclear Chem., 1958, 7, 38.

33. L. H. Jones, J. Chem. Phys., 1962, 36, 1209.

34. L. H. Jones, Inorg. Chem., 1963, 2, 777.

35. R. P. Mitra, D. V. S. Jain, A. K. Banerjee and K. V. R. Chari, J. Inorg. Nuclear Chem., 1963, 25, 1263.

36. Gmelin's Handbuck of Anorganischen Chemie, Iron 59B, Verlag Chemie, GmbH, Berlin, 1938, p. 903.

37. N. Targuge, Ann. Chem. Applic., 1926, 16, 407.

38. O. Baudisch, Science, 1948, 108, 443.

39. V. G. Belikov and V. N. Bernshtein, Sb. Nauchn. Dockl., 1960, 38.

40. J. H. Swinehart, Unpublished results.

41. L. Cambi, Ann. Chim. Applic., 1927, 17, 55.

42. I. M. Kolthoff and P. E. Toren, J. Amer. Chem. Soc., 1953, 75, 1197.

43. P. Zuman and M. Kabat, Chem. Listy., 1954, 48, 358.

44. J. H. Swinehart and P. A. Rock, Inorg. Chem., 1966, 5, 573.

45. D. X. West, Dissertation Abstr., 1965, 25, 5552.

46. G. Heppe, Arch. Pharm., 1856, 139, 57.

47. L. J. Simon and L. Piaux, Bull. Soc. Chim. Biol., 1924, 6, 477.

48. L. Cambi, Atti. Accad. Nazl. Lineei., 1912, 22, 376.

49. K. W. Loack and T. A. Turney, J. Inorg. Nuclear Chem., 1961, 18, 178.

50. L. Cambi, Atti. Accad. Nazl. Linceei., 1914, 23, 812.

51. K. W. Loack and T. A. Turney, J. Inorg. Nuclear Chem., 1961, 18, 179.

52. T. P. Avolini, Bull. Chim. Farm., 1930, 69, 713.

53. I. Fages, Compt. Rend., 1902, 134, 1143.

54. M. Z. Yampol'skii and B. E. Geller, Tr. Komis po Analit. Khin., 1963, 13, 78.

55. J. H. Swinehart and W. G. Schmidt, Inorg. Chem., 1969, 6, 232.

56. T. Weyl, Ber., 1875, 11, 2175.

57. A. Wilhelmy, Annalen, 1850, 81, 413.

58. Hartridge and Roughton, Proc. Roy. Soc., A, 1923, 104, 376.

59. Papers on most of these techniques are to be found in Discuss. Faraday Soc., 1954, 17, 114.

60. The papers read at this conference were published in Z. Elektrochem., 1960, 64.

61. Q. H. Gibson, J. Physiol., 1952, 117, 49.

62. A. Adams, Br. J. Anaesth., 1975, 47, 778.

63. G. Leigh, Br. J. Anaesth., 1975, 47, 745.

64. J. Tuzel, J. Clin. Pharmacol., 1974, 14, 444.

65. D. Yanson, A. Magness, W. Vise, J. Neurosurg., 1975, 43, 579.

66. D. W. Davies, D. Karas, D. J. Steward, and J. R. Munro, Can. Anaesth. Soc. J., 1975, 22, 547.

67. A. J. Merriefield and M. D. Blundell, Br. J. Anaesth., 1974, 46, 324.

68. R. D. Jack, Br. J. Anaesth., 1974, 46, 952.

69. S. K. Wolfe and J. H. Swinehart, Inorg. Chem., 1973, 14, 1049.

70. C. C. Johnson, Arch. Int. Pharacodyn. Ther., 1929, 35, 480.

71. P. Needleman, B. Jaschik and M. Johnson, J. Pharmacol. Exp. Ther., 1973, 187, 324.

72. W. I. K. Bissett, M. G. Burdon, A. R. Butler, C. Glidewell and J. Reglinski, J. Chem. Research, 1981.

73. H. Maltz. M. A. Grant and M. C. Navaroli, J. Org. Chem., 1971, 36, 363.

74. S. A. Cotton, F. A. Hart: The Heavy Transition Elements, Macmillan, 1975. F. A. Cotton, G. Wilkinson: Advanced Inorganic Chemistry, Interscience, 1966.

75. W. Hieber, R. Nast, G. Gehring, Z. Anorg. Ally. Chem., 1948, 256, 169.

76. K. G. Coulton, Coord. Chem. Rev., 1975, 14, 317.

77. J. Lingane, Electroanalytical Chemistry, Wiley and Sons, 1966.

78. G. Marr, B. Rockett, Practical Organic Chemistry, Van Nostrand, 1972.

79. D. Turnbull and S. H. Maron, J. Amer. Chem. Soc., 1943, 65, 212.

80. A. Wollenberger, Acta Chem. Scand., 1953, 7, 445.

81. E. Legal, Jahresberichte uber die Fortschritte der Chemie, 1883, 1648.

82. R. Pearson and R. L. Dillon, J. Amer. Chem. Soc., 1953, 75, 2439.

83. F. J. Kezdy, J. Jaz and A. Broylants, Bull. Soc. Chem. Belg., 1958, 67, 687.

84. E. S. Swinbourne, J. Chem. Soc., 1960, 2371.

85. E. S. Swinbourne, 'Analysis of Kinetic Data', Nelson, 1971.