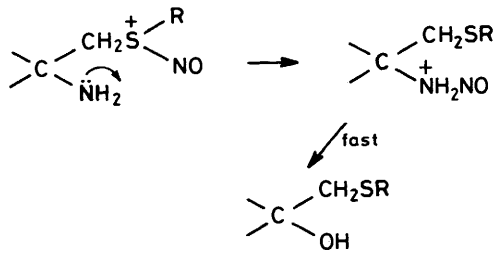
Kinetics and Mechanism of the Nitrosation of Thioproline: Evidence of the Existence of Two Reaction Paths

Albino Castro, Emilia Iglesias, J. Ramón Leis,* and José Vázquez Tato
Departamento de Química Física, Universidad de Santiago, E-Santiago de Compostela, Spain
Francisco Meijide and M. Elena Peña*
Facultad de Veterinaria, Aptdo. 280, 27071 Lugo, Spain

The kinetics of *N*-nitrosation of thioproline have been studied under a variety of experimental conditions. The experimental rate equation obtained in the absence of nucleophiles suggests that under these conditions nitrosation initially takes place at the sulphur atom, the nitroso group subsequently being transferred to the nitrogen atom. The fact that a primary isotope effect and general base catalysis are observed, together with the experimental rate equation, implies that the rearrangement is intramolecular, and that the rate-controlling step is the loss of a proton from the nitrogen atom of the *S*-nitrosated intermediate. Cl^-, Br^-, SCN^-, and thiourea all catalyse the reaction *via* the formation of the corresponding nitrosyl compounds, which react directly with the unprotonated thioproline nitrogen atom in both the negatively charged and neutral forms of the amino acid. The observed rate constants for these reactions are discussed in terms of the nature of the nitrosating agent and the substrate. In the case of Br^- and Cl^- the plot of reaction rate against concentration of catalyst levels off at high values of the latter, showing that the protonated *N*-nitrosamine intermediate is in the steady state. The characteristics of the curve, which provide a measure of the susceptibility of the nitrosamine to nucleophiles, show that this is much less than that of aromatic amines of similar basicity.

The best known *S*-nitrosation reactions[1] are those in which thiols (RSH) react in acid media with the usual nitrosating agents (NO^+, nitrosyl halides, *etc.*) to give the corresponding thionitrite esters.[2,3] NO^+ is significantly more effective than other nitrosating agents in these reactions, with a reactivity close to the diffusion-controlled limit.[3]

In the case of simple RSR sulphides, the absence of a good leaving group prevents the formation of *S*-nitrosated derivatives,[1] but there is nevertheless evidence that the sulphur atom plays a role in the *N*-nitrosation of sulphides like methionine and *S*-methylcysteine which contain an amino group. To explain the fact that the deamination of these two compounds by nitrous acid proceeds much faster than that of amines lacking the SR group, Meyer and Williams[4] suggested that nitrosation initially takes place at the sulphur atom, and that the *S*-nitrosated ion so formed then undergoes a rearrangement leading eventually to the final products. Their experimental data allow no decision whether the rate-controlling step is the formation of the *S*-nitrosated intermediate or the rearrangement, and although the observed first-order dependence on the concentration of amine suggests the latter to consist of the simple intramolecular process shown in Scheme 1, the possibility of a non-rate-controlling intermolecular rearrangement cannot be ruled out.



Scheme 1.

Transfer of the NO group from the sulphur to the nitrogen atom has also been invoked by Tahira *et al.*[5] to explain the acidity dependence of the *N*-nitrosation of thioproline (thiazolidine-4-carboxylic acid) and the fact that this reaction is again significantly faster than in the case of the non-thio analogue. Thioproline is a compound of considerable biological interest, and the corresponding *N*-nitroso compound (which since the amino group is secondary is the final product of its nitrosation[5]) is the main nitroso compound present in human urine.[6] This paper describes a comprehensive study of the kinetics of the nitrosation of thioproline, and offers evidence of there being two reaction paths.

Experimental

Thioproline (TP) was supplied by Fluka, and D_2O (99.77% deuterium) by the Spanish Junta de Energía Nuclear. Other commercial products used were obtained from Merck with the highest purity available. The ethyl ester of thioproline was synthesized by a procedure analogous to that described by Ratner and Clarke.[7]

Kinetic measurements were obtained by monitoring the u.v. absorbance (λ 240 or 265 nm) due to the nitroso compound in a Uvikon 820 u.v.-visible spectrophotometer with a thermostatted cell. Acidity was measured with a Radiometer model 82 pH-meter, equipped with GK2401C combined glass electrode. The acidity constants of the amino acid and its ethyl ester were determined potentiometrically using a Metrohm 645 multi-Dosimat automatic microburette.

Kinetic analysis was carried out using the integration method, with a large deficiency of nitrous acid (>20×) with respect to the other reagents. Equations of the form (1), where

$$\ln(A_\infty - A_t) = \ln(A_\infty - A_0) - k_1 t \qquad (1)$$

A_∞, A_t, and A_0 are the absorbances at infinite, t, and 0 times, respectively, and k_1 is the corresponding pseudo-first-order rate constant, were fitted to the experimental data using the algorithm of Davies *et al.*[8] and the satisfactory fit obtained (Figure 1) shows that under the conditions employed the reaction is first order in nitrous acid. Kinetic experiments were duplicated and results agreed to within 3%. Experiments were

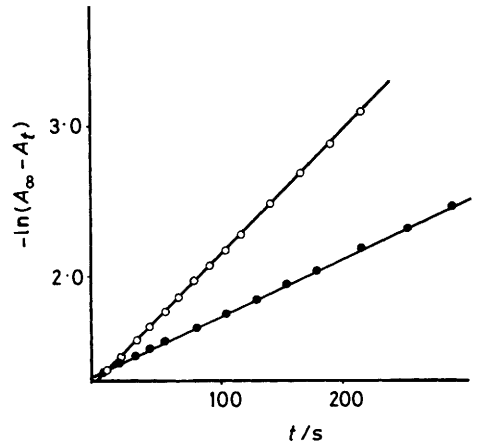


Figure 1. Typical first-order kinetics for the nitrosation of thioproline at 25 °C and *I* 0.2M, with [TP] 1.27 × 10^{-3}M, [Nit] 5.1 × 10^{-5}M, (○) at pH 1.09, (●) at pH 1.43

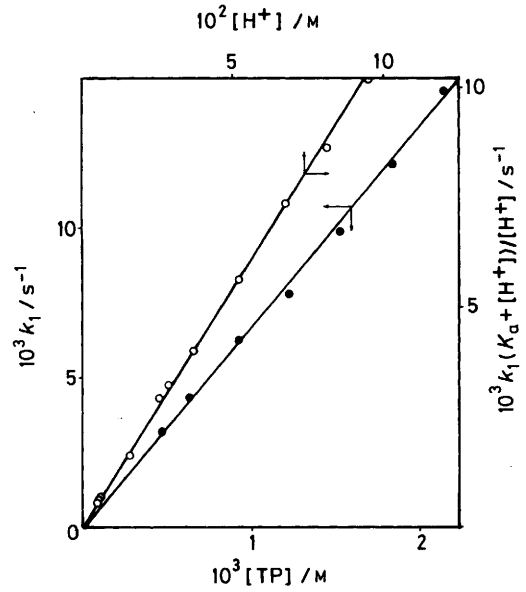


Figure 2. (●) Influence of the concentration of TP on the experimental first-order pseudo-constant of its nitrosation at pH 1.12; (○) influence of acidity on the experimental first-order pseudo-constant of the nitrosation of TP [equation (2)]: [TP] 1.27 × 10^{-3}M

carried out at 25 °C and constant ionic strength 0.2 mol dm^{-3} ($NaClO_4$) except those in which Cl^- was used, for which *I* was 1 mol dm^{-3}.

Results and Discussion

Reaction in the Absence of Nucleophiles.—Figure 2 shows typical results for how the rate of *N*-nitrosation of thioproline is affected by varying acidity between pH 1.02 and 2.31 and by varying the concentration of TP between 4.75 × 10^{-4} and 2.15 × 10^{-3} mol dm^{-3}. The observed first-order behaviour with respect to TP, HNO_2, and H^+ is represented in equation (2),

$$r = k_1[\text{Nit}] = \alpha[HNO_2][TP][H^+] = \beta[\text{Nit}][TP][H^+]^2/(K_a + [H^+]) \quad (2)$$

where [Nit] = $[HNO_2] + [NO_2^-]$ and K_a is the acidity constant of nitrous acid.[9] Fitting equation (2) to the totality of the experimental data yields a value of 88 ± 7 dm^6 mol^{-2} s^{-1} for β.

Table 1. Values of β [equation (2)] for the nitrosation of TP in D_2O under various experimental conditions

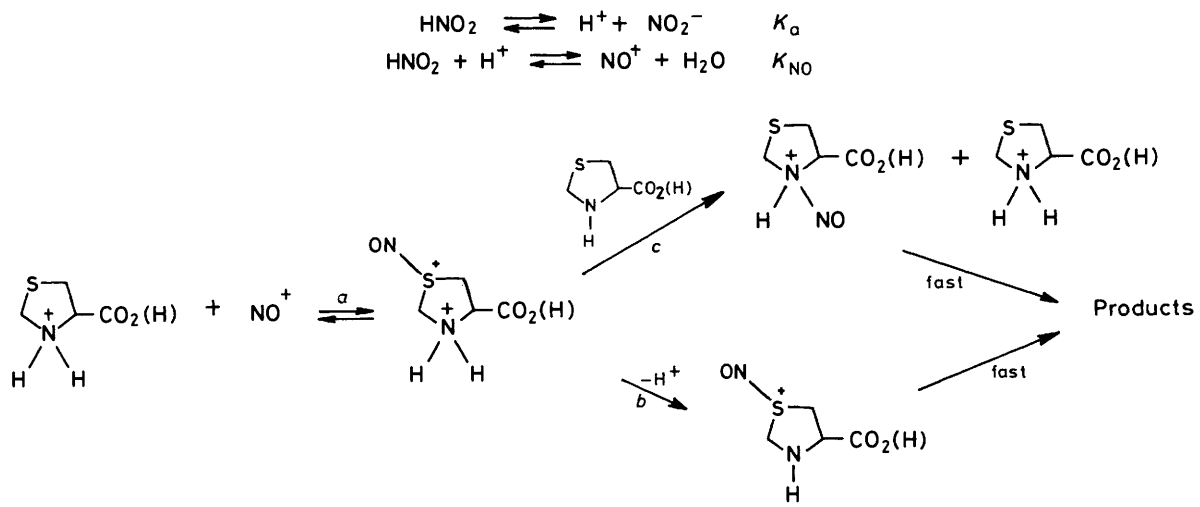
pD	10^3[TP]/mol dm^{-3}	β/dm^6 mol^{-2} s^{-1}
2.07	3.82	64.9
2.25	7.65	64.2
2.32	11.5	65.0
2.37	15.3	67.8
2.48	22.9	65.6
1.90	1.91	58.2
1.81	1.91	69.6
1.72	1.91	66.8
1.64	1.91	69.6
1.57	1.91	66.9

According to equation (2), the reaction rate is proportional to the total concentration of amine present in the medium regardless of whether the nitrogen atom is protonated or not, behaviour that is very different from that usually observed in the nitrosation or diazotization of amines.[10] Since the protonated nitrogen atom is not subject to electrophile attack by the nitrosating agent (presumably NO^+), equation (2) shows that nitrosation initially takes place at the sulphur atom. The alternatives that may be considered *a priori* for the subsequent transfer of the NO group to the nitrogen atom are illustrated in Scheme 2.

Equation (2) rules out the possibility that step *c* in Scheme 2 controls the reaction rate; this would result in second-order dependence on the concentration of amine. The rate-controlling step is therefore either step *a*, in which case it is impossible to distinguish kinetically whether the transfer of the nitroso group from sulphur to nitrogen is inter- or intra-molecular, or step *b*, in which case the proton transfer preceding the internal rearrangement makes the reaction subject to a primary isotope effect and general base catalysis. In order to decide between these two possibilities, we carried out kinetic measurements in D_2O at various acidities (pD = $pH_{measured}$ + 0.4[11]) using various concentrations of TP to yield a value 66 ± 3 dm^6 mol^{-2} s^{-1} for β_{D_2O} (see Table 1), which, bearing in mind that the concentration of NO^+ is 2.7 times greater in D_2O than in H_2O,[12] implies an isotope effect of k_H/k_D of 3.6. This value is typical for a primary isotope effect, and rules out the possibility that the rate-controlling step of Scheme 2 is step *a*, which involves no proton transfer. This conclusion is further supported by the kinetic results obtained in the presence of mono- and tri-chloro-acetate buffers, which were both found to catalyse the reaction (Figure 3).

The fact that the formation of the *S*-nitrosated intermediate is not the rate-controlling step explains why β is considerably smaller than the quite uniform values of 2 000—6 000 observed for reactions between NO^+ and many other substrates, which are accordingly considered as being diffusion-controlled.[13]

Reaction in the Presence of Nucleophiles.—According to Scheme 2, in which step *b* has now been established as rate controlling, halides, even if involved in the reaction, ought not to catalyse it because the equilibrium concentration of the *S*-nitrosated intermediate is unaffected by their presence (put another way, it is impossible to distinguish which is the effective nitrosating agent that reacts with the sulphur atom, though it is shown as NO^+ in Scheme 2). Experimentally, however, varying the concentration of Br^- between 0 and 0.2 mol dm^{-3} at acidities between pH 1.4 and 2.06 (Figure 4) showed that bromide ions have a strong non-linear catalytic effect, doubtless



Scheme 2.

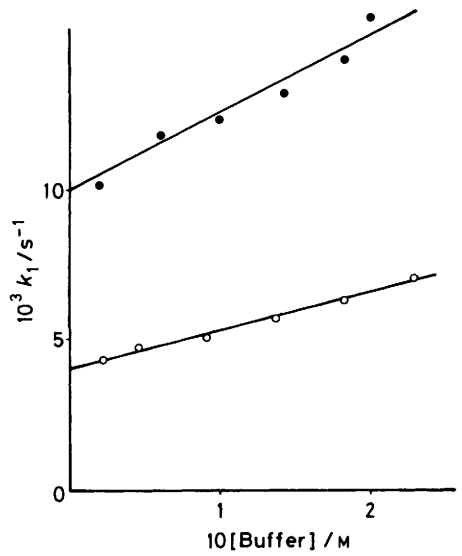


Figure 3. Influence of the concentration of buffer on the experimental first-order pseudo-constant of the nitrosation of TP at I 0.2M. (○) Monochloroacetate buffer at pH 1.88, [TP] 4.11 × 10^{-3}M; (●) trichloroacetate buffer at pH 1.08, [TP] 1.58 × 10^{-3}M

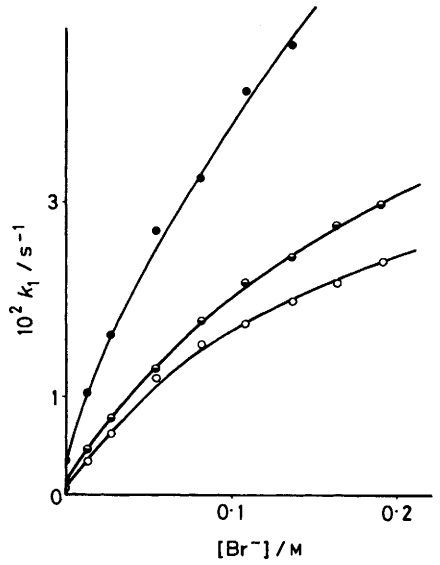


Figure 4. Influence of the concentration of Br^- on k_1 at I 0.2M for [TP] 9.50 × 10^{-4}M: (●) at pH 1.56, (◒) at pH 2.05, and (○) at pH 2.23

due to the action of NOBr. The curves of Figure 4, in which the intercepts at the origin indicate the experimental rate for the mechanism of Scheme 2, correspond to equation (3). The

$$k_1 = (A + B[Br^-])/(1 + C[Br^-]) \quad (3)$$

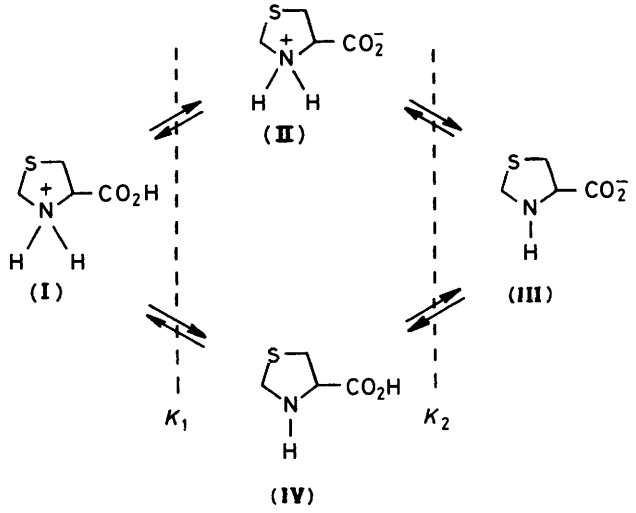
parameters A— C were estimated using the algorithm of Davies *et al.*[14]

The only explanation for the observed effects of Br^- is that in the presence of catalysts there is a second reaction path in which nitrosation does not take place at the sulphur atom but at the other nucleophilic centre, the nitrogen atom (this would not be the first time that the existence of two nucleophilic centres has been found to give rise to two different nitrosation mechanisms[15,16]). Of the four forms in which TP may be present in the medium (Scheme 3), the ones which are susceptible to electrophile attack at the nitrogen atom are those in which this atom is unprotonated, (III) and (IV). The concentrations of these species are given by equations (4) and (5), where K_e is the acidity constant of an ester of the amino acid,

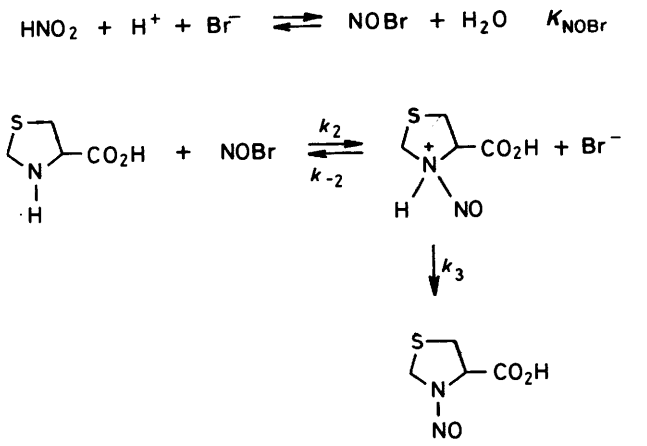
$$[(IV)] = K_e[TP]/(K_1 + [H^+]) \quad (4)$$

$$[(III)] = K_1K_2[TP]/[H^+](K_1 + [H^+]) \quad (5)$$

which is assumed to be equal to that of the form of the amino acid in which the acid group is protonated.[17] Since no values have been published for the constants of equations (4) and (5) for the working conditions used in the present study, they were determined potentiometrically at an ionic strength of 0.2 mol dm^{-3} (controlled with $NaClO_4$), the values obtained being pK_1 1.62, pK_2 5.79, and pK_e 4.01. At the acidities employed, (IV) predominates greatly over (III), >93% of the non-nitrogen-protonated amine being present in this form, and since the rate of reaction of NOBr with amines of this basicity is diffusion-controlled[18] it may be expected that only the reaction with (IV) has kinetic significance. The hypothetical reaction mechanism proposed for this reaction path is therefore shown in Scheme 4. The non-integer order of the reaction with respect to Br^-



Scheme 3.



Scheme 4.

(between 1 and 0) may be explained by supposing the protonated nitrosamine to be in the steady state as the result of $k_{-2}[Br^-]$ and k_3 being of similar magnitude, a situation that has been reported fairly frequently,[12,19,20] though not for aliphatic amines.

The mechanism in Scheme 4 implies that the catalytic term of the rate equation is given by equation (6). Identifying this with

$$k_1 = \frac{K_{NOBr}K_e k_2[H^+]^2[TP][Br^-]}{(K_a + [H^+])(K_1 + [H^+])(1 + k_{-2}[Br^-]/k_3)} \quad (6)$$

the corresponding terms of equation (3) yields equations (7) and (8). Figure 5 shows that, as predicted by equation (7), $[H^+]^2/$

$$B = \frac{K_{NOBr}K_e k_2[TP][H^+]^2}{(K_a + [H^+])(K_1 + [H^+])} \quad (7)$$

$$C = k_{-2}/k_3 \quad (8)$$

$B(K_a + [H^+])$ depends linearly on $[H^+]$, in the form of equation (9). K_1 and $k_2K_eK_{NOBr}$ may therefore be estimated by

$$\frac{[H^+]^2}{(K_a + [H^+])B} = \frac{K_1 + [H^+]}{K_eK_{NOBr}k_2[TP]} \quad (9)$$

fitting this equation to the experimental data. The result for K_1

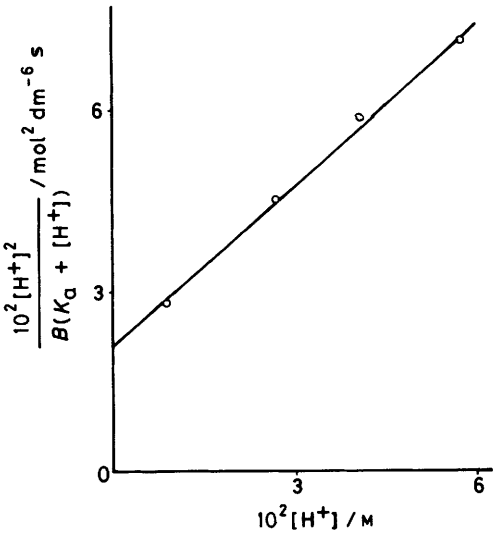


Figure 5. $[H^+]^2/B(K_a + [H^+])$ plotted against $[H^+]$ [equation (9)] for I 0.2M and [TP] 9.50 × 10^{-4}M (catalysis by Br^-)

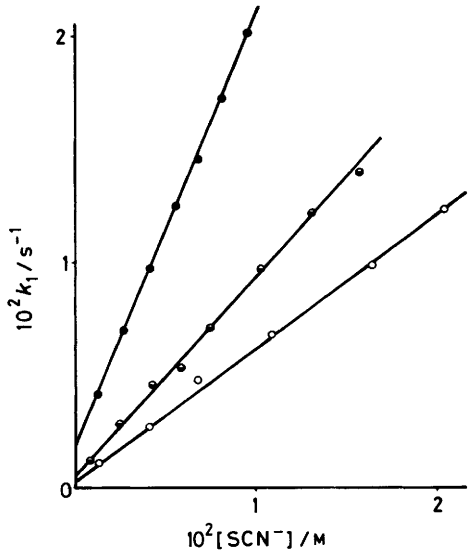


Figure 6. Influence of the concentration of SCN^- on k_1 at I 0.2M for [TP] 4.75 × 10^{-4}M: (●) pH 1.63; (◒) pH 2.22; (○) pH 2.60

gives the value of 1.64 for pK_1 (in excellent agreement with that determined potentiometrically); and when the value of K_{NOBr} [21] and the potentiometrically determined value of K_e are taken into account, the result for $k_2K_{NOBr}K_e$ yields 2.17 × 10^8 dm^3 mol^{-1} s^{-1} for k_2, a figure just slightly higher than those obtained for the reactions of NOBr with other secondary aliphatic amines. Furthermore, the experimental value of C, 5.9 ± 0.6 dm^3 mol^{-1}, is independent of pH, as predicted by equation (8). These findings jointly provide strong evidence in support of the mechanism proposed.

When instead of Br^- the nucleophile used was Cl^-, whose concentration was varied from 0 to 1 mol dm^{-3} (the ionic strength being maintained at 1 mol dm^{-3} throughout), the behaviour observed was analogous to that described above for Br^-, and the corresponding parameters are listed in Table 2. However, when SCN^- and thiourea (TU) were used (the concentration of SCN^- being varied from 1.4 × 10^{-3} to 2.8 × 10^{-2} mol dm^{-3} and that of TU from 2.5 × 10^{-5} to 2.5 × 10^{-4} mol dm^{-3}), plots of k_1 against $[X^-]$ were linear

Table 2. Values of the kinetic and thermodynamic constants of the nitrosation of TP in the presence of nucleophiles (X)

X	K_{NOX}/dm^6 mol^{-2}	$n^{24}_{Pearson}$	k_2/dm^3 mol^{-1} s^{-1}	(k_{-2}/k_3)/dm^3 mol^{-1}	k_4/dm^3 mol^{-1} s^{-1}	pK_1	I/mol dm^{-3}
Cl^-	1.1 × 10^{-3} (ref. 22)	4.37	8.1 × 10^8	1.2		1.48	1
Br^-	5.1 × 10^{-2} (ref. 21)	5.79	2.3 × 10^8	5.8	6.24 × 10^8	1.64	0.2
SCN^-	32 (ref. 23)	6.70	2.5 × 10^6		9.02 × 10^6	1.65	0.2
TU	5 000 (ref. 24)	7.27	2.1 × 10^4		1.68 × 10^5	1.65	0.2

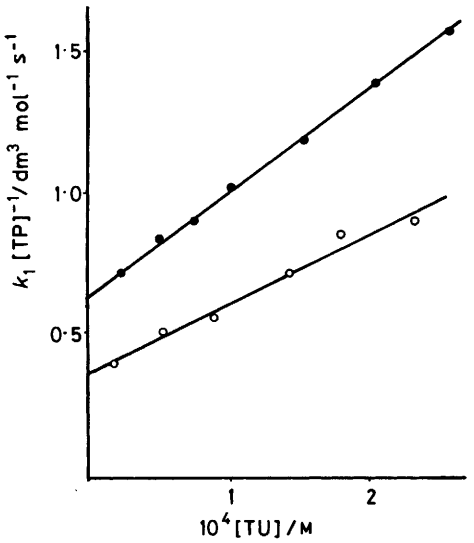


Figure 7. Influence of the concentration of TU on the experimental first-order pseudo-constant of the nitrosation of TP at I 0.2M, (●) at pH 2.08, and (○) at pH 2.30

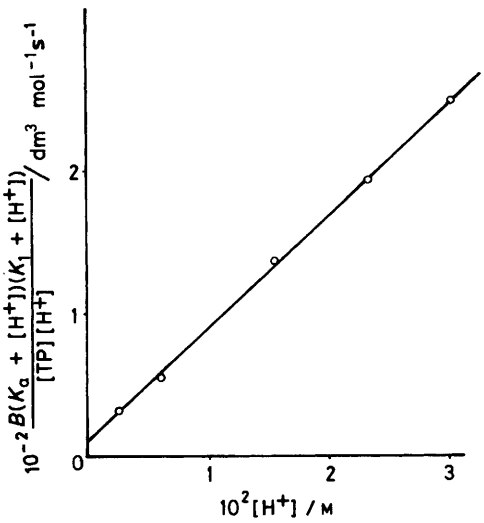
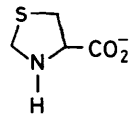


Figure 8. $B(K_1 + [H^+])(K_a + [H^+])/[H^+][TP]$ plotted against $[H^+]$ [equation (11)] for catalysis by SCN^- in the nitrosation of TP

(Figures 6 and 7). This behaviour differs from that observed in the nitrosation of anilines of similar basicity,[12,20] and shows that in the case of TP k_{-2} is much less sensitive to the degree of nucleophilicity of the catalyst, perhaps because TP is aliphatic. For SCN^- and TU, moreover, the catalysis observed at the highest pH values employed does not obey equation (6), being higher than predicted from experiments at higher acidity. Both NOSCN and $NOTU^+$ may react with TP significantly more slowly than the encounter rate and therefore discriminate between substrates of different basicities. If this is so, then for the minor form (**III**) (of pK_a 5.8) the rate constant may be very much greater than for the major form (**IV**) (of pK_a 4), so that both affect the kinetics of the reaction, the former *via* equation (10).



$$+ \text{XNO} \xrightarrow{k_4} \text{Products} \qquad (10)$$

The theoretical equation now obtained for catalysis by SCN^- and TU is therefore (11). Figure 8 shows for SCN^- that the

$$B = \frac{K_{NOX}K_e k_2[TP][H^+]^2}{(K_1 + [H^+])(K_a + [H^+])} + \frac{K_{NOX}K_1K_2k_4[TP][H^+]}{(K_1 + [H^+])(K_a + [H^+])} \qquad (11)$$

linear dependence of $B(K_1 + [H^+])(K_a + [H^+])/[H^+]$ on $[H^+]$ predicted by this equation is in fact observed, and the same is true for $NOTU^+$. The slope of the plot in Figure 8 is determined by the reaction with the major form (**IV**), and the intercept at the origin by the reaction with (**III**), which is thus hardly significant in the most acid media but channels *ca.* 50% of the entire reaction at pH 2.6. The values of k_2 and k_4 obtained from Figure 8 (Table 2) show that the more basic form (**III**) does indeed react faster than (**IV**), and that, as is natural, the difference is greater for thiourea than for SCN^-.

Since (**III**) and (**IV**) have different charges, different reactivity will also be found for diffusion-controlled reactions. Experiments were therefore carried out with Br^- at higher pH than those used previously (one such series is shown in Figure 4). Table 2 shows the value of k_4 obtained by fitting equation (11) to the experimental data. The ratio of 2.7 between k_4 and k_2 is within the range of expected values for the rate constants of the encounter of a polar electrophile with negative and neutral species.

Table 2 shows that the rate constant for the reaction between the nitrosating agent NOX and the substrate increases with the electronegativity of X, as is natural in view of the increasing positive charge density on the electrophilic NO group. In the case of NOCl and NOBr the reaction is thought to be practically diffusion-controlled when the basicity of the substrate is similar to that of TP,[13,18] though it is not clear why the limiting rate should be significantly slower for aliphatic amines (*ca.* 4 × 10^7 dm^3 mol^{-1} s^{-1})[18] than for aromatic compounds (*ca.* 2 × 10^9 dm^3 mol^{-1} s^{-1}).[13] In this respect, TP seems to be intermediate between the two groups of substrates studied hitherto, perhaps because the sulphur atom may induce a greater degree of sp^2 hydridization in the nitrogen atom than is present in aliphatic analogues without sulphur, and this in turn may affect the encounter rate.

Since the k_{-2} step is a reaction between a nucleophile and an electrophile, the ratio k_{-2}/k_3 should increase with the nucleophilicity of the former; for reactions with non-aromatic amines it has been found[12,25,26] that a good measure of nucleophilicity is provided by Pearson's n,[27] and that for a given amine the

susceptibility of the reaction to this effect may be measured by the slope ρ of the graph of $\log(k_{-2}/k_3)$ against n for various nucleophiles. We have already seen that in the case of TP we have been unable to estimate k_{-2}/k_3 for SCN^- and TU because of the very insensitivity of k_{-2} to nucleophilicity, further evidence of which is provided by comparing the ratio of 4.9 between the figures for Cl^- and Br^- in the TP reaction with the ratio of 55 found in the case of *N*-methyl-*N*-nitrosoaniline.[25] The value of ρ may nevertheless be obtained as the slope of the plot of $\log(K_{NOX}k_2)$ against n, for since $K_{NOX}k_2k_3/k_{-2}$ must be the same for all the NOX species the ratio k_{-2}/k_3 varies proportionally with $K_{NOX}k_2$. The slope calculated from the data for Br^-, SCN^-, and thiourea (the figure for Cl^- must be excluded because of its having been determined at a different ionic strength) is 0.6, which is much smaller than the figures of 1.4 for *N*-methylaniline[25] and 1.1 for 1-naphthylamine,[12] and suggests that protonated *N*-nitrosothioproline is more electrophile than protonated *N*-nitrosamines derived from aromatic amines with pK_a values similar to that of thioproline.

Acknowledgements

One of us (E. I.) thanks the Spanish Ministry of Education and Science for a Research Training Grant.

References

1 D. L. H. Williams, *Chem. Soc. Rev.*, 1985, **14**, 171.
2 P. Collings, K. Al-Mallah, and G. Stedman, *J. Chem. Soc., Perkin Trans. 2*, 1975, 1734.
3 L. R. Dix and D. L. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 1984, 109.
4 T. A. Meyer and D. L. H. Williams, *J. Chem. Soc., Chem. Commun.*, 1983, 1067.
5 T. Tahira, M. Tsuda, K. Wakabayashi, M. Nagao, and T. Sugimura, *Gann*, 1984, **75**, 889.
6 (*a*) H. Ohshima, M. Friesen, I. O'Neill, and H. Bartsch, *Cancer Lett.*, 1983, **20**, 183; (*b*) M. Tsuda, T. Hirayama, and T. Sugimura, *Gann*, 1983, **74**, 331.
7 S. Ratner and H. T. Clarke, *J. Am. Chem. Soc.*, 1937, **59**, 200.
8 J. Casado, M. Mosquera, A. Rivas, M. F. Rodríguez Prieto, and J. A. Santaballa, *Comput. Chem.*, 1983, **7**, 209.
9 A. Castro, M. Cid, and J. A. Santaballa, *J. Chem. Res. (S)*, 1986, 60.
10 (*a*) B. C. Challis and J. A. Challis, in 'The Chemistry of Amino, Nitroso and Nitro Compounds and their Derivatives,' ed. S. Patai, Wiley, New York, 1982, ch. 26; (*b*) D. L. H. Williams, *Adv. Phys. Org. Chem.*, 1983, **19**, 381.
11 P. Salomaa, L. L. Schaleger, and F. A. Long, *J. Am. Chem. Soc.*, 1964, **86**, 1.
12 J. Casado, A. Castro, E. Iglesias, M. E. Peña, and J. Vázquez Tato, *Can. J. Chem.*, 1986, **64**, 133.
13 J. H. Ridd, *Adv. Phys. Org. Chem.*, 1978, **16**, 1.
14 P. R. Adby and M. A. H. Dempster, in 'Introduction to Optimization Methods,' Chapman and Hall, London, 1974.
15 J. Casado, A. Castro, J. R. Leis, M. Mosquera, and M. E. Peña, *J. Chem. Soc., Perkin Trans. 2*, 1985, 1859.
16 A. Castro, E. Iglesias, J. R. Leis, M. E. Peña, J. Vázquez Tato, and D. L. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 1986, 1165.
17 H. Rossoti, in 'The Study of Ionic Equilibria,' Longman, New York, 1978, p. 48.
18 A. Castro, J. R. Leis, and M. E. Peña, *J. Chem. Res. (S)*, 1986, 216.
19 A. Woppmann and H. Sofer, *Monatsh. Chem.*, 1972, **103**, 163.
20 M. R. Crampton, J. T. Thompson, and D. L. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 1979, 18.
21 H. Schmid and M. G. Fouad, *Monatsh. Chem.*, 1957, **88**, 631.
22 H. Schmid and E. Hallaba, *Monatsh. Chem.*, 1956, **87**, 560.
23 G. Stedman and P. A. E. Whincup, *J. Chem. Soc.*, 1963, 5796.
24 K. Al-Mallah, P. Collings, and G. Stedman, *J. Chem. Soc., Dalton Trans.*, 1974, 2469.
25 I. D. Biggs and D. L. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 1975, 107.
26 G. Hallett and D. L. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 1980, 624.
27 R. G. Pearson, H. Sobel, and J. Songstad, *J. Am. Chem. Soc.*, 1968, **90**, 319.

Received 20*th May* 1986; *Paper* 6/976