Kinetics and Mechanism of Oxidation of Aromatic Acetals With N-Chlorosuccinimide

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ABSTRACT

The kinetics of oxidation of aromatic acetals by N–chlorosuccinimide (NCS) in acetonitrile medium results in the formation of corresponding esters. The reaction is first order with respect to NCS and acetals. A negative effect of [succinimide] is observed, while [Cl⁻] shows negligible effect on reaction velocity. Increase in ionic strength increases the rate. Increase in polarity of the medium decreases the rate. The rate constants correlate well with Taft's σ* values, the reaction constant being negative. A mechanism involving hydride-ion transfer from the acetal to the oxidant in the rate-determining step has been suggested.

Keywords: kinetics, mechanism, NCS, acetal.

INTRODUCTION

The chemistry of N-halo compounds has evidenced considerable interest, as they are sources of halonium cations, hypohalite species and N–anions which act as both bases and nucleophiles. As a result, they interact with a wide range of functional groups, effecting an array of molecular transformations[1,2]. N–chlorosuccinimide (NCS), one such N–halocompound is reported to be a mild and stable oxidant for selective oxidation[3]. This potent oxidant is of special interest for studying reaction mechanisms as it behaves both as chlorinating and oxidizing agent[4-6]. The oxidative capacity of this analytical reagent has been widely utilized for the quantitative determinations of large number of inorganic and organic substances in solution prompted us to undertake the present kinetic studies.

Acetals find versatile applications as new initiators for cationic polymerization of isobutyl vinyl ether[7], in asymmetric heterocyclic addition reactions[8], as sensitisers[9], precursor of acidic drugs[10] etc. Oxidation of acetals to esters brought about by various oxidizing agents under different sets of conditions has been reported in the literature[11-16]. However, there seems to be no report on the oxidation kinetics of aromatic a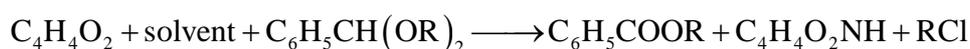cetals using NCS. Hence, we report the results of the investigations on the mechanistic and kinetic aspects of oxidation of acetals by NCS. The objectives of the present investigations are to elucidate a suitable mechanism, put forward an appropriate rate law, ascertain the reactive species, assess the relative reactivities of the substrates, establish the isokinetic relationships using thermodynamic parameters evaluated and to compare the reactivity.

EXPERIMENTAL

NCS was prepared by the reported method. The purity of NCS was checked iodometrically through its active chlorine content. The substrates benzaldehyde di-ethyl acetal, benzaldehyde di-n-propyl acetal, benzaldehyde di-n-butyl acetal, benzaldehyde di-isobutyl acetal and benzaldehyde di-isoamyl acetal were prepared in the laboratory and their purities were checked by spectral methods. Triply distilled water was used in preparing all aqueous solutions. All the other chemicals were of analytical grade.

The reaction was carried out under pseudo-first order conditions, where [acetal] >> [NCS]. In a glass stoppered reagent bottle at constant temperature appropriate amounts of acetal, sodium perchlorate and acetonitrile (to keep the total volume constant for all runs) were

taken and thermostated at 50° C for thermal equilibrium. A measured amount of NCS solution, also thermostated at the same temperature was rapidly added to the mixture. The progress of the reaction was monitored by iodometric determination of unreacted NCS in a measured aliquot of the reaction mixture at different intervals of time. The first-order rate constants calculated were reproducible within ± 3%.

STOICHIOMETRY AND PRODUCT ANALYSIS

The reaction mixtures containing varying compositions of NCS and acetal were kept at equilibrium in presence of 0.1 M sodium perchlorate for 24 h. The iodometric determination of unreacted NCS in the reaction mixture showed that one mole of acetal has consumed one mole of the NCS according to equation

$$C_4H_4O_2 + solvent + C_6H_5CH(OR)_2 \longrightarrow C_6H_5COOR + C_4H_4O_2NH + RCl$$

R = ethyl, n–propyl, n–butyl, isobutyl, isoamyl.

The reaction mixture containing excess of [acetal] over [NCS] was kept overnight. The products in the reaction mixture were extracted several times with water followed by diethyl ether. The combined ether extracts was evaporated and the product ester was identified by the TLC, IR and NMR spectral data.

RESULTS AND DISCUSSION

With the substrate in excess, at constant ionic strength and temperature, the $[NCS]_0$ is varied. Plots of log [NCS] vs time are linear (r > 0.99) indicating a first order dependence of the rate on $[NCS]_0$. Though the first-order rate coefficient increases with increase in $[NCS]_0$, in each kinetic run strictly it follows first-order kinetics. The pseudo first-order rate constants (k_1) calculated from the slope are given in Table-1. The pseudo first-order rate constant increases with the increase in the substrate concentration. The plot of log k_1 vs log [acetal] for all the compounds studied have been found to be linear with slope nearly unity indicating first-order dependence on [acetal]. Variation of ionic strength (affected by addition of $NaClO_4$) of the medium increases the rate indicating the involvement of ion-dipole species in the rate determining step.

The reaction is studied in acetonitrile–water compositions. The rate decreases with increase in dielectric constant of the medium. The effect of solvent on the reaction kinetics has been described in detail in the well-known monographs of Moelwyn-Hughes[17], Laidler[18], Benson[19], Frost and Pearson[20], Amis[21] and Entelis and Tiger[22]. For the limiting case of zero angle of approach between two diploes or an ion- dipole system, Amis has shown that a plot of log k vs 1/D gives a straight line, with a negative slope for a reaction between a negative ion and a dipole or between two dipoles, while a positive slope results for a positive ion-dipole reaction. The observed dielectric effect shows that the reaction is between positive ion and dipole species (Table - 4). The negative effect of addition of succinimide (SA) on the rate constant is given in table-5.

The possibility of radical involvement in the reaction is ruled out, as the addition of acrylonitrile in the reaction mixture developed no turbidity. The reactions are studied at different temperatures and the rate constants at 40, 45, 50, 55 and 60° C are calculated to compute E_a, $\Delta H^{\#}$, $\Delta S^{\#}$, $\Delta G^{\#}$ and log A in the oxidation of acetal and these activation parameters are recorded in table-6.
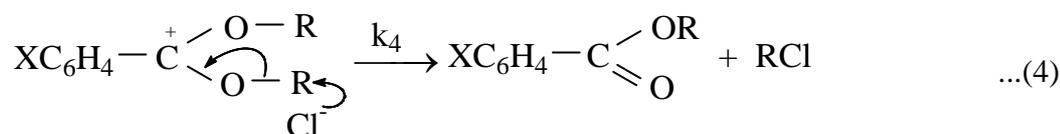
MECHANISM AND RATE LAW

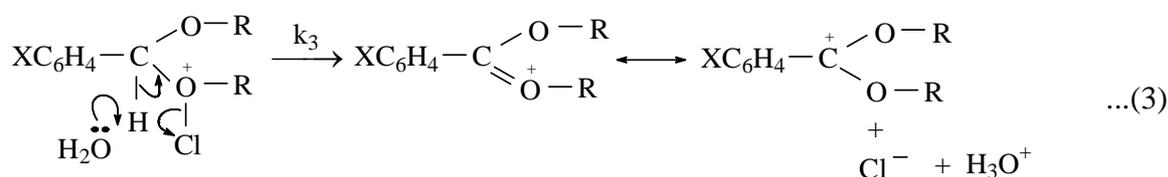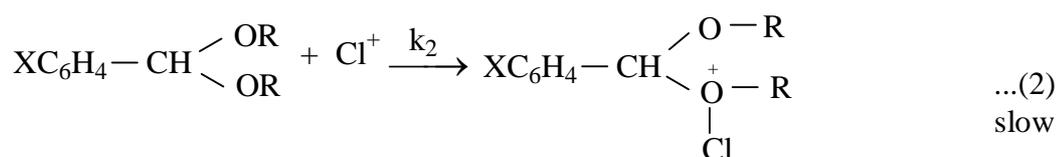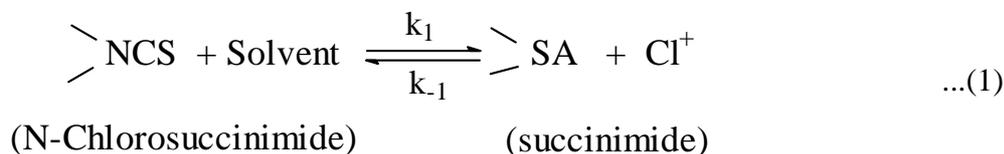The oxidizing species in NCS may be HOCl, H_2OCl^+, cationic chlorine (i.e.,) Cl^+ and NCS itself. NCS, if taken as active species, it is unable to explain the negative effect of succinimide on the reaction rate[23]. Since the rate is invariant with Cl^- the possibility of involvement of Cl_2 is ruled out.

Earlier Br^+ has been postulated as effective oxidizing species[24]. Based on the

above experimental findings in the absence of chloride ion, among the other species Cl^+ can be assumed as active oxidizing species to account for the observed ionic strength and solvent effect

and the following mechanism is proposed where in the more polar acetonitrile medium Cl^+ is formed and act as the active oxidant species.

$$NCS + Solvent \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} SA + Cl^+ \qquad ...(1)$$

(N-Chlorosuccinimide)   (succinimide)

$$XC_6H_4-CH \begin{matrix} OR \\ OR \end{matrix} + Cl^+ \xrightarrow{k_2} XC_6H_4-CH \begin{matrix} O-R \\ \overset{+}{O}-R \\ | \\ Cl \end{matrix} \qquad \begin{matrix} ...(2) \\ slow \end{matrix}$$

$$XC_6H_4-C \xrightarrow{k_3} XC_6H_4-C \longleftrightarrow XC_6H_4-\overset{+}{C} \qquad ...(3)$$
$$Cl^- + H_3O^+$$

$$XC_6H_4-\overset{+}{C} \begin{matrix} O-R \\ O \end{matrix} R \xrightarrow{k_4} XC_6H_4-C \begin{matrix} OR \\ O \end{matrix} + RCl \qquad ...(4)$$

$$K = \frac{k_1}{k_{-1}} = \frac{[SA][Cl^+]}{[NCS][Solvent]} \qquad ...(5)$$

Since the solvent is in large excess equation (5) can be written as

$$K = \frac{k_1}{k_{-1}} = \frac{[SA][Cl^+]}{[NCS]} \qquad ...(6)$$

Hence the equilibrium concentration of the reactive oxidizing species is

$$[Cl^+] = \frac{k_1[NCS]}{k_{-1}[SA]} \qquad ...(7)$$

The rate of the reaction is

$$\frac{-d[NCS]}{dt} = k_2 \left[XC_6H_4 - CH(OR)_2 \right][Cl^+] \qquad \text{...(8)}$$

Substituting for $[Cl^+]$ from equation(7)

$$\frac{-d[NCS]}{dt} = \frac{k_1 k_2 \left[XC_6H_4 - CH(OR)_2 \right][NCS]}{k_{-1}[SA]} \qquad \text{...(9)}$$

The above rate equation satisfactorily explains the first-order dependence of rate with respect to [acetal], [NCS] and inverse dependence of rate on [SA]. The above mechanism is isoelectronic with Westheimer[25] mechanism for the oxidation of alcohols by chromic acid and is well supported by oxidation of ethers[26].

EFFECT OF SUBSTITUENTS ON THE REACTION RATE

As an extension of the present investigation, the kinetics of oxidation of alkyl substituted acetals are studied at different temperatures. The second order rate constants and thermodynamic parameters calculated using Eyring's equation is given in Table - 6. The rate data are analyzed by Taft's equation. In table-6, the entropy of activation is not constant for all the substituents. A plot of $\Delta H^{\#}$ vs $\Delta S^{\#}$ gives a straight line. However Exner[27] criticized the validity of such a linear correlation between $\Delta H^{\#}$ and $\Delta S^{\#}$, as these quantities depend on each other. When measurements at two temperatures have been made, the experimental data can be treated by the following equation[28].

log $k_2(T_2)$= a + b log $k_2(T_1)$

When $T_2 > T_1$.
A straight line is obtained with good correlation (r = 0.99) when log $k_{(323\ K)}$ is plotted against log $k_{(333\ K)}$. It shows the operation of unified mechanism for all the reactions in this series. The iso-kinetic temperature (β) obtained from the slope is 412 K.

The reactivity of different acetals were found to increase in the order ethyl acetal < n–propyl acetal < n–butyl acetal < isobutyl acetal < isoamyl acetal. The electron donors accelerate the reaction rate since the rate- determining step proceeds with the development of positive charge in the transition state[29]. This probably indicates the transition state to possess a small carbonium ion character. In the present investigation Taft's plot of log k vs σ* is found to be linear at 323 K with ρ* = −3.047. This negative value of ρ* suggests the development of electron deficient reaction centre[30-32] in the activated complex. The observed results thus indicate a hydride ion transfer from acetal to NCS in the rate determining step. The negative entropy of activation also supports the above mechanism. When two reacting molecules combine to form a single activated complex, the restrictions on their motion obviously increase[33], for they can no longer move independently. This results in large negative entropy of activation.

Table 1: Effect of variation of [acetal] on the rate constant for the oxidation of acetals by NCS at 323 K.

[NCS] = 6.0×10^{-3} M   [NaClO$_4$.H$_2$O] = 1.0×10^{-1} M   CH$_3$CN = 100%

[C$_6$H$_5$CH(OR)$_2$] × 10^2(M)	$k_1 \times 10^4$ (s^{-1})				
	R = ethyl	R = n-propyl	R = n-butyl	R = isobutyl	R = isoamyl
6.0	06.29	07.12	07.62	07.86	09.84
7.0	07.22	08.41	08.51	08.92	11.21
8.0	07.95	09.54	09.87	10.27	13.23
9.0	09.20	10.75	11.24	11.42	14.80
10.0	10.14	11.89	12.54	13.18	16.52

Table 2: Effect of variation of [NCS] on the rate constant for the oxidation of acetals by NCS at 323 K.

$[C_6H_5CH(OR)_2] = 8.0 \times 10^{-2}\,M$ $[NaClO_4.H_2O] = 1.0 \times 10^{-1}\,M$ $CH_3CN = 100\%$

[NCS] ×10³(M)	$k_1 \times 10^4$ (s⁻¹)				
	R = ethyl	R = n-propyl	R = n-butyl	R = isobutyl	R = isoamyl
6.0	07.95	09.54	09.87	10.27	13.23
7.0	09.34	10.23	10.96	12.99	15.24
8.0	10.68	11.62	12.24	14.83	17.52
9.0	12.14	12.88	13.68	16.84	19.21
10.0	13.28	13.96	14.89	18.74	21.23

Table 3: Effect of ionic strength on the rate constant for the oxidation of acetals by NCS

$[C_6H_5CH(OR)_2] = 8.0 \times 10^{-2}\,M$ $[NCS] = 6.0 \times 10^{-3}\,M$ $CH_3CN = 100\%$

[NaClO₄.H₂O] × 10²M	$k_1 \times 10^4$ (s⁻¹)				
	R = ethyl	R = n-propyl	R = n-butyl	R = isobutyl	R = isoamyl
05.0	07.14	08.20	08.82	09.02	11.56
10.0	08.31	09.54	09.87	10.27	13.23
15.0	09.42	10.20	10.71	11.38	14.56
20.0	10.40	11.31	11.42	12.46	15.82

Table 4: Effect of solvent composition on the rate constant for the oxidation of acetals by NCS

$[C_6H_5CH(OR)_2] = 8.0 \times 10^{-2}\,M$ $[NCS] = 6.0 \times 10^{-3}\,M$ $[NaClO_4.H_2O]=1.0\times10^{-1}\,M$

CH₃CN–H₂O (%) (v/v)	$k_1 \times 10^4$ (s⁻¹)				
	R = ethyl	R = n-propyl	R= n-butyl	R = isobutyl	R = isoamyl
100 – 0	07.95	09.54	09.87	10.27	13.23
98 – 2	06.63	08.31	08.71	09.15	11.83
96 – 4	05.04	06.74	07.52	07.73	10.52
94 – 6	03.71	05.43	06.47	06.35	09.16
92 – 8	02.89	04.45	05.44	05.42	07.82

Table 5: Effect of succinimide on the rate constant for the oxidation of acetals by NCS

$[C_6H_5CH(OR)_2] = 8.0 \times 10^{-2}\,M$ $[NCS] = 6.0 \times 10^{-3}\,M$

$[NaClO_4.H_2O] = 1.0 \times 10^{-1}\,M$ $CH_3CN = 100\%$

[SA] × 10³ (M)	$k_1 \times 10^4$ (s⁻¹)				
	R = ethyl	R = n-propyl	R = n-butyl	R = isobutyl	R = isoamyl
0.0	07.95	09.54	09.87	10.27	13.23
1.0	07.33	08.66	09.08	09.28	12.28
2.0	06.16	07.42	07.98	08.23	11.09
3.0	05.01	06.23	06.91	07.36	10.36
4.0	04.18	05.23	05.93	06.37	09.44

Table 6: Rate constants and activation parameters of the oxidation of acetals by NCS

$[C_6H_5CH(OR)_2] = 8.0 \times 10^{-2}\,M$ $[NCS] = 6.0 \times 10^{-3}\,M$ $[NaClO_4.H_2O] = 1.0 \times 10^{-1}\,M$ $CH_3CN = 100\%$

$C_6H_5CH(OR)_2$	$k_2 \times 10^3$ (dm⁻³ mol s⁻¹)					E_a (kJ/mol)	$\Delta H^{\#}$ (kJ/mol)	$\Delta S^{\#}$ (J/mol/K)	$\Delta G^{\#}$ (kJ/mol)
	313 K	318 K	323 K	328 K	333 K				
R = ethyl	04.54	06.29	10.01	13.67	19.67	64.27	61.59	-93.17	91.68
R = n-propyl	05.56	07.89	11.92	17.27	22.64	62.28	59.59	-97.88	91.21
R = n-butyl	06.35	09.06	12.31	18.57	23.26	57.48	54.79	-112.49	91.13
R = isobutyl	06.95	09.45	12.82	19.23	24.95	56.60	53.91	-114.49	91.02
R = isoamyl	08.96	12.42	16.50	23.14	30.26	52.98	50.29	-123.98	90.34

REFERENCES

1. Banerji K Kalyan. Kinetics and mechanism of oxidation of substituted benzylamines by N–chlorosuccinimide. Journal of Chemical Society Perkin Transactions II. 1988;6:1015-1019.

2. Evans Dennis F, Upton and Mark W. Studies on singlet oxygen in aqueous solution. Part 1. Formation of singlet oxygen from hydrogen peroxide with two electron oxidants. Journal of Chemical Society Dalton Transaction. 1985;6:1141-1145.

3. Agulla B, Antelo JM, Arce F and Parajo M. Kinetics and mechanism of the reaction of N-chlorosuccinimide with I$^-$ and OH$^-$. International Journal of Chemical Kinetics. 2005;37(4):243-252.

4. Kumar Ashutosh, Singh Abhishek and Singh Khagesh K. Kinetic and mechanistic study of N–chlorosuccinimide oxidation of 2–methyl butanol–1 in the presence of osmium tetroxide as homogeneous catalyst in aqueous alkaline solution. Asian Journal of Chemistry. 2010;22(2):1296-1300.

5. Ashutosh kumar and abishek Singh. Kinetics and mechanism of Os (VIII)- catalysed oxidation of 2–methyl propanol by N–chlorosuccinimide in aqueous alkaline medium. Asian Journal of Chemistry. 2010;22(2):1291-1295.

6. Sathiyanarayanan K, Madheswari T and Lee Chang Woo. Behavior of N–chlorosuccinimide towards diphenyl selenide: A kinetic and mechanistic study. Journal of Industrial and Engineering Chemistry. 2007;13(3): 420- 423.

7. Kotaro Satoh, Masami Kamigaito and Mitsuo Sawamoto. Aromatic acetals as new initiators for cationic polymerisation of isobutylvinyl ether. Macromolecules 2000;33(3):748-753.

8. Patricia Gizecki, Robert Dhal, Céline Poulard, Pascal Gosselin and Gilles Dujardin. Novel use of N–benzoyl–N–O–acetals as N–acylimine equivalents in asymmetric heterocycloaddition. An extended enantioselective pathway to p–benzamido aldehydes. Journal of Organic Chemistry. 2003;68(11):4338-4344.

9. Evensen JF, Sommer S, Rimington C and Moan J. Photodynamic therapy of C_3H mouse mammary carcinoma with haematoporphyrin di-ethers as sensitizers. British Journal of Cancer. 1987;55(5):483-486.

10. Vicco Domenick, Callery and Patrick S. Metabolic conversion of 2–propylpentanal acetals to valproic acid in vitro. Model prodrugs of carboxylic acid agents. Drug Metabolism and Disposition. 1989;17(5):513-517.

11. Mathiyalagan N. Correlation analysis in the study of oxidation kinetics of aromatic acetals with N–bromosuccinimide in acetonitrile medium. Journal of Indian Chemical Society. 2011;88(6):865-868:

12. Ramakrishnan PS. Kinetics and mechanism of oxidation of aromatic acetals by acidic pyridinum chlorochromate. Asian Journal of Chemistry. 2000;12(4): 1096-1100:

13. Basheer Ahamed KA, Sheik Dawood S, Baskaran P and Nambi K. Reactions of aliphatic acetals with N–chlorosaccharin: a kinetic study. Journal of Indian Chemical Society. 1996;73(12): 687-688.

14. Chockalingam P, Ramakrishnan PS, Arulraj SJ and Nambi K. Kinetics and mechanism of oxidation of aromatic acetals by ceric ammonium nitrate in acetonitrile medium. Journal of Indian Chemical Society. 1992;69(5):247-250.

15. Nambi K, Ahamed KA Basheer and Arulraj SJ. Chromic acid oxidation of aromatic acetals in aqueous acetic acid medium. A kinetic and mechanistic study. Journal of Indian Chemical Society. 1988;65(2):85-87.

16. Ahamed KA Basheer, Nambi K and Arulraj SJ. Kinetics of chromic acid oxidation aliphatic acetals in aqueous acetic acid medium. Indian Journal of Chemistry. 1987;26A(8):672-674.

17. Moelwyn Hughes EA. The kinetics of reactions in solutions. Clarendon Press, Oxford. 1947. E.A. Moelwyn-Hughes, Physical Chemistry 2nd edn. Pergamon , New York; 1961.

18. Laidler KJ and Landskroener PA. Trans Faraday Soc. 1957;52:200. Laidler KJ, Reaction Kinetics. Pergamon New York. 1963.

19. Benson SW. The foundations of chemical kinetics. McGraw-Hill, New York. 1960.

20. Frost AA and Pearson RG. Kinetics and Mechanism 2nd edn. Wiley, New York. 1961.

21. Amis ES. Solvent effects on reaction rates and mechanisms. Academic New York. 1966.

22. Entelis SG and Tiger RP. Reaction kinetics in the liquid Phase. Wiley, New York. 1976.

23. Kalyan K Banerji. Kinetics and mechanism of the oxidation of substituted benzylamines by N–chlorosuccinimide Journal of Chemical Society Perkin Transaction II. 1988; 1015-1021.

24. Sivakamasundari S and Ganesan R. Kinetics and mechanism of the bromination of aromatic compounds by N–bromosuccinimide in solution International Journal of Chemical Kinetics. 1980;12(11):837-850.

25. Westheimer FH. The kinetics of oxidation of 2–deutropropanol by chromic acid. Journal of American Chemical Society. 1949;71:25-28.

26. Deno NC and Neil H Potter. Mechanism and synthetic utility of the oxidative cleavage of ethers by aqueous bromine. Journal of American Chemical Society. 1967;89:3550-3555.

27. Exner O, Concerning the isokinetic relationship. Nature 1964; 201: 488-490;

28. Claude F. Bernasconi. Techniques of chemistry; Investigation of rates and mechanisms of reactions. John Wiley and Sons. 1986;6(4):298-299

29. Rajagopalan T, Sabapathy Mohan, Mannathasamy Gopalakrishnan and Mahalingam Sekar. Kinetics and mechanism of OS (VIII)-catalysed oxidation of some substituted trans-cinnamic acids by chloramine-T in alkaline medium-A Non-linear Hammett plot. Tetrahedron, 1994;50(37):10945-10954.

30. Mathiayalagan N and Sridharan R. Oxidation of benzyl ethers by N–bromosuccinimide: A kinetic and mechanistic study. Journal of Indian Chemical Society. 2006;83:434-437.

31. Seema Kothari, Anupma Agarwal and Kalyan K Banerji. Kinetics and mechanism of oxidation of primary alcohols by n-bromo-3,5-dinitrobenzamide. Indian Journal of Chemistry. 1986;25A:722-724.

32. Mahadevappa DS and Anandha S. Oxidation of primary alcohols by Sodium N–bromosulphonamide: A kinetic study. Indian Journal of Chemistry. 1985;24A:589-593.

33. Gould ES, Mechanism and structure in organic chemistry. Holt, Rinehart and Winston New York. 1964;181.