The Isomerization of Trityl Isonitrile to Trityl Cyanide

in Acetonitrile: Effect of Anions

TOR AUSTAD and JON SONGSTAD

Chemical Institute, University of Bergen, N-5000 Bergen, Norway

Trityl isonitrile isomerizes quantitatively to trityl cyanide in acetonitrile and nitromethane at room temperature. In solvents of very low ionizing power like carbon tetrachloride, cyclohexane, and various petroleum ethers, trityl isonitrile is perfectly stable for days.

The activation parameters for the rearrangement in pure acetonitrile at 25°C, $\Delta H^{\neq} = 23 \pm 1$ kcal mol^{-1} and $\Delta S^{\neq} = 0 \pm 4$ cal mol^{-1} deg^{-1}, suggest the isomerization to be of the S_N1 type mechanism. Salts of the perchlorate ion show a considerable catalytic effect, as expected for an S_N1 type reaction.

Minute amounts of tetraphenylarsonium cyanide, azide, chloride, or iodide exert a very distinct rate depression. At concentrations of these salts higher than 10^{-3} M, no isomerization could be detected. The possible reasons for this exceptional salt effect, and salt effects on S_N1 reactions in aprotic media in general, are discussed.

The rearrangement of isonitriles to cyanides was recognized more than a century ago.[1] Due to the fundamental work by Rabinovitch and co-workers,[2] this reaction has received much attention during the last decade. Recently, two comprehensive reviews have appeared.[3,4]

Although the free energy difference between cyanides and isonitriles is considerable, $\simeq 15$ kcal/mol in favour of the more stable cyanides,[5] the rates of isomerization of most organic isonitriles are exceedingly small at room temperature. The rather few kinetic studies reported so far have therefore been performed at elevated temperatures.

With regard to the mechanism of the isonitrile-cyanide rearrangement, Rabinovitch *et al.*[4] have suggested a structure for the activated complex in which the development of the new $C-C$ bond is nearly synchronous with the breaking of the $N-C$ bond, and Casanova and co-workers[5] have shown that retention of stereochemical integrity at the migrating carbon atom occurs. Likewise, lack of carbon skeleton rearrangement during the isomerization of cyclobutyl isonitrile, and very low sensitivity of the rates of isomerization to variation in *para* substituents in aryl isonitriles, support the view that little charge separation develops in the transition state.[6] Extended Hückel calcula-

tions on the isonitrile-cyanide rearrangement, however, suggest a considerable increase in positive charge on the migrating carbon atom in the transition state.[7]

Recently, Yamada and co-workers [8] have shown that isomerization of isonitriles to cyanides may occur with racemization of configuration, and have suggested a radical rearrangement to account for the lack of stereochemical integrity. Shaw and Pritchard [9] have proposed a radical-chain process to explain their observation that certain isonitriles isomerize readily in the presence of di-t-butyl peroxide.

This paper is concerned with a study on the isomerization of an isonitrile where the mechanism most probably is of the S_N1 type. Trityl isonitrile isomerizes quantitatively at room temperature in acetonitrile and nitromethane at a rate which is conveniently measured by following the disappearance of the isonitrile peak at 2126 cm^{-1} using IR liquid cells. The rate of the isomerization was found to be independent of the initial concentration in the 1×10^{-2} M to 5×10^{-2} M region, as anticipated for a unimolecular reaction, and the reaction could be followed for several half-lives. As an initial concentration of the isonitrile of 2.00×10^{-2} M was found to be the most convenient one when 0.1 cm cells were used, the rates of isomerization were accurately determined at this concentration. In acetonitrile at 35°C, the half-life was close to 30 min. In nitromethane, isodielectric with acetonitrile, the rate of isomerization was found to be some 30 % higher than in acetonitrile. The ionizing power of nitromethane is known to be a little higher than that of acetonitrile.[10] No isomerization could be detected in solvents like carbon tetrachloride, cyclohexane, or various petroleum ethers. These solvents were therefore used as crystallization media for the isonitrile.

The activation parameters for the rearrangement in pure acetonitrile at 25°C, calculated from rates at 25.0°C, 35.0°C and 46.0°C, $\Delta H^{\pm} = 23 \pm 1$ kcal mol^{-1} and $\Delta S^{\pm} = 0 \pm 4$ cal mol^{-1} deg^{-1}, are in the range expected for an S_N1 type reaction.[11] The rate constants are listed in Table 1. Addition of tetraphenylarsonium perchlorate or lithium perchlorate in concentrations higher than 10^{-4} M showed a considerable catalytic effect, the former salt exerting the more pronounced effect, probably due to its higher degree of dissociation in acetonitrile. Hydroquinone and m-dinitrobenzene were found not to have any detectable effect upon the rates of isomerization.
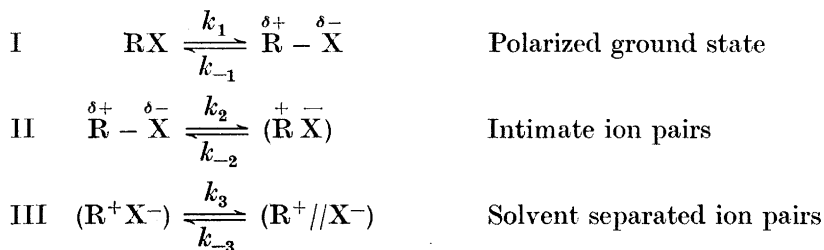
The addition of tetraphenylarsonium azide, iodide, cyanide, or chloride showed a very distinct rate depression, even at concentrations of these salts as low as 10^{-6} M to 10^{-5} M. For concentrations of these salts higher than 10^{-3} M, no isomerization could be detected, even after several hours. Trityl isonitrile was found to be stable even in acetonitrile in the presence of tetraphenylarsonium perchlorate and tetraphenylarsonium azide, 1.15×10^{-2} M and 2×10^{-3} M, respectively. A small amount of ionic azide was thus found to completely depress the catalytic effect exerted by the perchlorate ions. At this step it may be recalled that trityl isonitrile can be synthesized in close to 100 % yield from trityl chloride and tetramethylammonium dicyanoargentate in acetonitrile.[12] Traces of ionic chloride or excess onium dicyanoargentate probably make this synthetic route possible by preventing the isonitrile from rearranging.
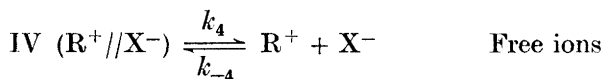
Table 1. First order rate constants, k_1, for the isomerization of trityl isonitrile to trityl cyanide. Initial concentration of trityl isonitrile in all runs $= 2.00 \times 10^{-2}$ M (As $=$ Ph$_4$As).

Solvent	Temp.°C	Added salt		$k_1 \times 10^4$
c-C$_6$H$_{12}$	35.0			$\ll 10^{-3}$
CCl$_4$	35.0			$\ll 10^{-3}$
MeNO$_2$	35.0			4.73
MeCN	25.0			0.77
»	35.0			3.35
»	46.0			10.6
»	35.0	LiClO$_4$	1.5×10^{-4} M	3.8
»	»	»	1.5×10^{-3} M	4.6
»	»	»	1.5×10^{-2} M	5.2
»	»	»	1.5×10^{-1} M	~ 43
»	»	AsClO$_4$	1×10^{-5} M	3.6
»	»	»	1×10^{-4} M	4.0
»	»	»	1×10^{-3} M	5.2
»	»	»	1×10^{-2} M	7.0
»	»	AsCl	1×10^{-6} M	2.3
»	»	»	2×10^{-6} M	1.9
»	»	»	5.2×10^{-6} M	0.67
»	»	AsI	2×10^{-6} M	3.2
»	»	»	5×10^{-6} M	2.0
»	»	AsCN	1×10^{-5} M	0.82
»	»	AsCN AsN$_3$ AsCl AsI	1×10^{-3} M	No reaction
»	»	AsN$_3$ $+$ AsClO$_4$	2×10^{-3} M 1.15×10^{-2} M	No reaction

The catalysis exerted by perchlorates on this reaction is in accordance with the usual salt effect on $S_N 1$ type reactions.[11] Although the present data are insufficient to allow an accurate determination of the b-value in the Winstein equation, the data suggest a value of 60 to 70 for the perchlorates, depending upon cation employed. A b-value of this order of magnitude in acetonitrile at room temperature is quite high. As Fava and co-workers[13] have pointed out, the Winstein b-value appears to be higher the more ionic the transition state.

It is generally accepted that the mechanism of the $S_N 1$ reaction is very complex and involves at least the following consecutive equilibria, where each of the species present may be the most important one, depending upon sub-strate, nucleophile, solvent, ionic strength, *etc.*:[14]

$$\text{I} \qquad \text{RX} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \overset{\delta+}{\text{R}} - \overset{\delta-}{\text{X}} \qquad\qquad \text{Polarized ground state}$$

$$\text{II} \qquad \overset{\delta+}{\text{R}} - \overset{\delta-}{\text{X}} \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} (\overset{+}{\text{R}} \overset{-}{\text{X}}) \qquad\qquad \text{Intimate ion pairs}$$

$$\text{III} \quad (\text{R}^+\text{X}^-) \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} (\text{R}^+//\text{X}^-) \qquad\qquad \text{Solvent separated ion pairs}$$

IV $(R^+//X^-) \underset{k_{-4}}{\overset{k_4}{\rightleftharpoons}} R^+ + X^-$ Free ions

The simple electrostatic theory and the empirical extension of the Debye-Hückel treatment both predict linear relationship between the logarithm of the rate constant and the ionic strength.[15] Experimentally, this relationship is rarely experimentally verified, while a linear relationship between the rate constant and the ionic strength is very often experienced,[18] and is the basis of the Winstein equation.

The rate depressions exerted by ionic azide, chloride, iodide, and cyanide are therefore quite surprising in view of the extensive experimental evidence reported in favour of the positive specific salt effect on S_N1 reactions. The rather high b-value of perchlorates obtained in this work suggests the transition state for the trityl isonitrile-trityl cyanide rearrangement to be quite ionic.

Recently, Bunton and co-workers [16] and Bunnett and Ech [17] have stressed the importance of considering separately the specific salt effects on S_N1 reactions exerted by salts of nucleophilic and non-nucleophilic anions. For S_N1 reactions in completely non-aqueous solvents, as in the case reported in this work, the effect due to nucleophilic ions will be quite different from the effect of these ions on solvolysis reactions where protic solvents are present as reactants and are able to depress the nucleophilicity, especially of small anions.[18] The rate decelerating effect by ionic azide, chloride, iodide, and cyanide ions may thus be due to the ability of these ions to stabilize species, which themselves are not sufficiently ionic to undergo rearrangement, and thereby to prevent further ionization necessary for isomerization, or to increase the internal return to the unreactive ground state.

As nucleophilic anions in concentrations less than 10^{-2} % of that of the substrate are, in the present case, capable of exerting a measurable depression on the rate of isomerization, one can safely conclude that there cannot be any important interaction between these ions and trityl isonitrile in its ground state. The determination of activity coefficients of substrates in various solvents in the presence of salts may thus not lead to the origin of large negative salt effects on S_N1 reactions.[19] When trityl isonitrile is partly polarized or exists as non-reactive ion pairs, there is undoubtedly some positive charge on the phenyl groups which may interact with the nucleophilic anions. In this connection it is interesting to note that very small or even negative b-values in the Winstein equation may be observed when the substrate being solvolyzed contains several phenyl groups. If the species involved in equilibrium IV were of any importance, trityl isonitrile should isomerize with a positive salt effect in the presence of ionic chloride and iodide, form trityl azide in the presence of ionic azide,[20] and suffer a distinct rate depression in the presence of ionic cyanide due to the common ion effect.[21] No trityl azide was found when tetraphenylarsonium azide was added to trityl isonitrile, even after prolonged periods. Traces only of this product would have been detected due to the high extinction coefficient of trityl azide at 2102 cm^{-1}. Furthermore, the rate depression exerted by the cyanide ion in dilute solutions of tetraphenylarsonium cyanide was found to be of the same order of magnitude as that exerted

by the corresponding chloride, iodide, and azide. The rate depressions observed must be due to the free ions, and not to dipole-dipole interactions between ion pairs,[22] as tetraphenylarsonium salts are known to be completely dissociated in acetonitrile in the concentrations applied in this work.

There are reports in the literature on negative salt effect on $S_N 1$ reactions. Fava and co-workers [23] have noted that the rate of isomerization of 4,4'-dimethylbenzhydryl thiocyanate in 95 % aqueous acetone decreases with increasing concentration of sodium thiocyanate. The hydrolysis of trityl acetate shows a distinct rate depression on addition of salts of nucleophilic anions.[24] It is interesting to note that, several years ago, Ingold and co-workers[25] found an exceptionally strong rate depression when studying unimolecular reactions in sulfur dioxide in the presence of nucleophilic common ions. It appears now as if this effect is not entirely due to the common ion effect. The difference between nucleophilic and non-nucleophilic anions as regards the dissociation of $S_N 1$ type substrates may be part of the reason why trityl halides and trityl pseudohalides are known to be very little ionized in dipolar aprotic solvents, contrary to trityl perchlorate.[26,27]

An extreme negative salt effect as found in this work does not seem to have been encountered previously. This effect may, as indicated above, be due to the increased nucleophilicity of small ions in dipolar aprotic solvents. It is furthermore known that the stability of adducts and complexes is greatly increased when going from protic solvents, or aprotic solvents containing protic reactants, as is the case in solvolysis reactions, to completely non-aqueous dipolar solvents.[28] The possible stabilizing effect on anionic adducts [29] of large non-polarizable counter ions, such as the tetraphenylarsonium cation applied in the present experiments, may be an additional factor to explain the magnitude of the negative salt effect.

One possible explanation might be that the effect is due to some interaction between the polarizable nucleophiles and the isonitrile triple bond or the terminal carbon atom, to prevent trityl isonitrile from ionization. Addition of minute amounts of trans-[Pt(py)$_2$I$_2$], however, to a solution of trityl isonitrile, in acetonitrile caused the rearrangement to be completed within 3 to 4 min. This catalysis is probably due to the well-documented reactivity of isonitriles to Pt(II)-substrates.[30,31] Similarly, silver cyanide, in a heterogeneous reaction with trityl isonitrile in acetonitrile, causes a nearly instantaneous isomerization.[32]

Obviously, the exceptional salt effect observed in this work may be due to a very special mechanism for the trityl isonitrile-trityl cyanide rearrangement. However, the solvent effect and the catalysis by perchlorates strongly support the view that the mechanism is of the $S_N 1$ type.

Further studies on salt effects on the $S_N 1$ reaction in non-aqueous solvents are in progress in this laboratory.

EXPERIMENTAL

Solvents. Acetonitrile "Baker Analyzed" reagent was purified by distillation from phosphorus pentoxide and finally from calcium hydride as reported previously.[12] Cyclohexane, Fluka *purum*, was distilled twice from calcium hydride. Carbon tetrachloride

was of spectroscopic grade. Nitromethane, Fluka *puriss.*, was used without further purification. Various petroleum ethers were dried with sodium.

Materials. Trityl isonitrile was made from purified trityl chloride and tetramethylammonium dicyanoargentate.[12] Crystallized from petroleum ether (80 – 100°C), and finally from cyclohexane, the product had m.p. 136°C. $\nu_{CN}(CCl_4) = 2216$ cm^{-1}, $\Delta\nu_{\frac{1}{2}} = 11$ cm^{-1}, $A = 1.0 \times 10^4$ M^{-1} cm^{-2}. Trityl cyanide was made according to Budde and Potempa.[33] M.p. (cyclohexane) 128°C. $\nu_{CN}(CCl_4) = 2239$ cm^{-1}, $\Delta\nu_{\frac{1}{2}} = 8$ cm^{-1}, $A = 5.5 \times 10^2$ M^{-1} cm^{-2}. Trityl azide was made in near quantitative yield from trityl chloride and excess sodium azide in acetonitrile. After filtration and evaporation of the solvent, the product was crystallized from methanol and finally from cyclohexane. M.p. 67°C. $\nu_{N_3}(CCl_4) = 2102$ cm^{-1}, $\Delta\nu_{\frac{1}{2}} = 10$ cm^{-1}, $A = 1.36 \times 10^4$ M^{-1} cm^{-2}.

Even concentrated solutions of these trityl derivatives in carbon tetrachloride did not show any absorption in the 3300 – 3600 cm^{-1} range. The products were therefore not measurably contaminated by trityl carbinol.

Tetraphenylarsonium chloride, iodide, cyanide, and azide were obtained pure and dry as reported previously.[34] *Trans*-[Pt(py)$_2$I$_2$] was made according to Kauffman.[35]

The melting points are corrected.

Experimental procedure. The rate of isomerization was determined by measuring the rate of disappearance of the isonitrile peak at 2126 cm^{-1} in the various solvents. Generally the reactions could be followed for two to three half-lives, and the logarithmic rate plots were completely linear throughout. The rates in pure acetonitrile, from which the activation parameters were calculated, are believed to have an accuracy better than ± 3 %. The other rate data are not supposed to be better than ± 5 %. The rate data in Table 1 refer to an initial concentration of the isonitrile of 0.0200 M.

Addition of an amount of *trans*-[Pt(py)$_2$I$_2$], equivalent to 4.8×10^{-4} M, to a 2×10^{-2} M solution of trityl isonitrile in acetonitrile at 35°C caused the isonitrile peak to disappear within 3 to 4 min.

IR instruments. The rates of isomerization were determined with a Unicam SP 200G Infrared Spectrophotometer. The integrated extinction coefficients of trityl isonitrile, trityl cyanide, and trityl azide in carbon tetrachloride were calculated from measurements performed with a Perkin-Elmer 225 Grating Infrared Spectrophotometer.

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