

**1021. The Rearrangement of Aromatic N-Nitroamines. Part III.¹
The Acid-catalysed Rearrangement of N-Nitroaniline.**

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Kinetic, product, and tracer studies have been made of the acid-catalysed rearrangement of isotopically normal and ²H-labelled *N*-nitro- to *o*- and *p*-nitro-aniline over a wide range of acidity. The results are consistent with an intramolecular mechanism involving isomerisation to an *N*-nitrite and migration to the *para*-position by way of an *ortho*-linked *C*-nitrite. Other mechanisms are discussed.

(1) *Background*.—The *N*-nitro-derivatives of arylamines (nitroamines) readily rearrange to the *ortho*- and *para*-*C*-isomers when treated with acid. Experiments designed to capture disproportionation products from typical nitroamines under rearrangement conditions indicated that the rearrangement was intramolecular,²⁻⁴ and recent tracer studies,^{1,5} have shown the rearrangement of *N*-nitro-aniline and *p*-toluidine to be intramolecular under restricted sets of experimental conditions, although an intermolecular component has been claimed for the rearrangement of *N*-methyl-*N*-nitroaniline.⁶ Of special importance was the demonstration¹ that *N*-nitroaniline yielded *p*-nitroaniline by an intramolecular route, for this implies that the migrating group spanned widely separated sites without becoming kinetically free.

The purpose of our present work with *N*-nitroaniline, the simplest aromatic nitroamine, was to attempt to decide between suggested mechanisms for the nitroamine rearrangement; to determine whether the reaction was intramolecular over a wide range of reaction conditions; and to discover any similarities to the benzidine rearrangement.⁷ There is no reason why one mechanism should operate over the entire acidity range, from acetate buffers to concentrated mineral acids, for which rearrangement can be effected.

(2) *Kinetics of Rearrangement*.—The kinetics were studied over the range 1.7M- to 3.6M-perchloric acid at 25°. The rate of formation of products was of the first order in substrate, as shown by the variation of the rate with *N*-nitroaniline concentration at a constant acidity, and the accurate dependence on a first-order law when a large excess of the catalysing-acid was used. In the absence of acid, the rate of rearrangement was negligible. Results are in Table I.

TABLE I.

Kinetics of rearrangement of *N*-nitroamine in aqueous HClO₄ and H₂SO₄ at 25°.

	Substrate concn., 1.5 × 10 ⁻⁴ M.							
(a) 10 ⁴ k ₁ (sec. ⁻¹)	1.2	1.6	3.5	4.4	7.4	10.5	12.7	21.1
[HClO ₄] (M)	1.68	1.88	2.22	2.52	2.92	3.16	3.30	3.56
-H ₀	0.62	0.72	0.89	1.04	1.20	1.32	1.38	1.53
	Acid concn., 2.22M.							
(b) 10 ⁴ k ₁ (sec. ⁻¹)	3.5	3.4	3.5	3.6	3.5			
10 ⁴ [Substrate] (M)	0.6	0.9	1.5	3.0	5.0			
	Substrate concn., 2 × 10 ⁻⁴ M.							
(c)* 10 ⁴ k ₁ (sec. ⁻¹)	1.02	1.58	2.80	6.48	8.77	14.78	20.8	
[H ₂ SO ₄] (M)	1.83	2.11	2.62	3.31	3.43	3.94	4.22	
-H ₀	0.67	0.81	1.06	1.38	1.44	1.66	1.78	

* We thank Miss A. M. White and Mr. P. Heslop for these measurements.

¹ Part II, Brownstein, Bunton, and Hughes, *J.*, 1958, 4354.

² Orton *et al.*, *J.*, 1905, **87**, 393; 1908, **93**, 725; 1929, 915.

³ Hollemann, Hartogs, and Van der Linden, *Ber.*, 1911, **44**, 704.

⁴ Hughes and Jones, *J.*, 1950, 2678.

⁵ Geller and Dubrova, *Zhur. obschchei Khim.*, 1960, **30**, 2646.

⁶ White and Golden, *Chem. and Ind.*, 1962, 138.

⁷ Banthorpe, Hughes, and Ingold, *J.*, 1964, 2864.

A plot of $\log k_1$ against $-H_0$ for perchloric acid was linear, with a slope of 1.35 ± 0.05 . For 1.8—4.0M-sulphuric acid, a similar plot had a slope of 1.25. The rate was measured in 1.84M- $H_2SO_4-H_2O$ and in a $D_2SO_4-D_2O$ solution of the same concentration and 99.8% isotopic purity. The values of the rate constants were 3.45×10^{-5} and 11.4×10^{-5} sec.⁻¹, respectively, *i.e.*, $k_{D_2O}/k_{H_2O} = 3.3$.

These results exclude most chain processes, as well as reactions in which one substrate molecule nitrates another,^{5,8} and they indicate that in this acidity range the initial step is a pre-equilibrium protonation of the substrate: the same conclusion was reached for the *N*-methylated homologue under quite different conditions.⁹ As the substrate is a fairly strong acid,* the protonated form must be even stronger, and so it is not surprising that the rate of proton transfer from it to a solvent molecule is greater than the rate of the competing rearrangement.

The steep Hammett slope suggests an *A1*-type decomposition of the protonated intermediate,¹⁰ as does the large solvent isotope-effect.¹¹ Inasmuch as such correlations have any value, the second is probably more reliable for it is known that steep Hammett slopes in related rearrangements can be due to ionic-strength effects;¹² such effects probably account for the different Hammett slopes with sulphuric and perchloric acids. Our acidities were above those at which ionic strength can be taken to control properties of solutions independently of the nature of the ionic composition, and for this reason we did not add salts to build up constant, formal, ionic strengths in our kinetic work.

(3) *Products of Rearrangement*.—These could be measured over a much wider range of conditions than could be covered by the kinetics, although there is some overlap at the low acidities (see Table 2). At the lower acidities, the addition of up to 50% by volume of ethanol (to ensure dissolution of the substrate) did not change the product ratio.

TABLE 2.
Products of rearrangement of *N*-nitroaniline at 0°.

Acid *	<i>o</i> -Nitro-aniline (%) †	Acid *	<i>o</i> -Nitro-aniline (%) †
74% $H_2SO_4-H_2O$ (16.1M)	95	72% $HClO_4-H_2O$ (11.2M)	91
60% "	92	61% "	86
52% "	88	50% "	75
44% "	81	37% " (4.8M)	72
36% "	81	26% "	70
25% "	78	18% " (2.5M)	70
83% w/w $H_3PO_4-H_2O$	96	Aq. M- $HClO_4$	66
Saturated HCl-ether	77	Aq. 0.5M- $HClO_4$	70
BF_3, Et_2O	57		

* Concentrations are w/w. † The percentage of *o*-nitroaniline in the rearrangement products: the remainder is the *para*-isomer.

These reactions were not clear-cut. Rearrangement products were recovered in greater than 95% of the theoretical yield at high acidities, but in only about 60% yield from 3M- or less concentrated acid. They consisted entirely of the *ortho*- and the *para*-isomer: no *m*-nitroaniline was detected. At concentrations of less than 3M and at temperatures above 0°, much tar was formed.

* Dependence on H_0 , rather than on a complicated function of H_0 and H_- , presumably arises because $H_- > pK_a$ under the reaction conditions.

⁸ Hückel, "Theoretical Principles of Organic Chemistry," Elsevier, Amsterdam, 1955, Vol. I, p. 265.

⁹ W. N. White, Klink, Lazdius, Hathaway, Golden, and H. S. White, *J. Amer. Chem. Soc.*, 1961, **83**, 2024.

¹⁰ Bunnett, *J. Amer. Chem. Soc.*, 1961, **83**, 4956, 4968, 4973, 4978.

¹¹ Long *et al.*, *J. Amer. Chem. Soc.*, 1957, **79**, 2362; 1958, **80**, 4162.

¹² Banthorpe, Hughes, Ingold, and Roy, *J.*, 1962, 3294.

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Early experiments were performed without additives but, when it was realised that nitrous acid could be present and might destroy the products to give spurious *ortho* : *para* ratios, some rearrangements were carried out in the presence of sodium azide. A two-fold molar excess of this almost entirely inhibited tar formation even at the lowest acidities, but it did not alter the rearrangement rate in 1.3—3.6M-perchloric acid; it increased the percentage recovery of nitroanilines only by a few units; it changed the *ortho* : *para* ratio similarly in a direction favouring more *ortho*-isomer. Larger excesses of azide did not cause appreciable further change, and so any free nitrous acid must have been destroyed before it could attack the substrate or rearrangement products. Furthermore the additive could not have abstracted nitrite ion from the protonated substrate to an appreciable extent.

In the absence of azide, a small percentage of disproportionation to nitrous acid could be detected polarographically¹³ at acidities greater than 10M-sulphuric acid, but none could be detected colorimetrically at lower acidities. No free amine or product of benzidine type could be detected by paper chromatography, and no nitrate ion (or species derived from this in strong acids) could be detected by polarography or colorimetry at any acidity in the range studied. Some products of side reactions were isolated: in a reaction with *ca.* M-acid an unidentified yellow compound was obtained in about 5% yield, and traces of nitrobenzene were detected over the whole range of acidities if ethanol was present as a co-solvent: nitrophenols were isolated in yields of several units per cent in experiments without added azide. The nitrophenols and the nitrobenzene may have resulted from the decomposition of a diazonium salt formed by attack of nitrous acid on the rearrangement products. Thus, for high acidities, a satisfactory product balance was achieved, but at low acidities up to 30% of the reaction mixture was not accounted for. These unidentified products are now being studied. Whatever their nature, we know (see section 8) that they did not interfere with the method of analysis of the rearrangement products.

When the potassium salt of *N*-nitroaniline was added to >10M-acids much tar was formed, nitrous fumes were evolved, and the percentage of *ortho*-isomer fell by about 10 units below the corresponding figures in Table 2. Presumably intermolecular nitrosation and subsequent oxidation occurred in such reactions.

Interesting colour phenomena appeared when *N*-nitroaniline was added to solutions more than 8M in either sulphuric or perchloric acid: a sequence of yellow, green, blue, turquoise, violet, light red, and almost colourless was obtained. Such colours appeared also with added azide (and then more rapidly) and so could not be attributed to reactions involving nitrogen oxides derived from nitrous acid; but addition of ascorbic acid completely suppressed them. The colour changes took place during periods of minutes in acidity regions where the rearrangement would be expected to be almost instantaneous. No electron spin resonance signal could be detected from these solutions. Less spectacular colours had been previously observed^{2,14} and were believed to indicate mesomeric intermediates, but it seems that the colours must have been due to some side reaction in our examples. Similar colours during benzidine rearrangements have been tracked down to oxidation products.¹⁵

On addition of *N*-nitroaniline to 18M-sulphuric acid there was a violent reaction, nitrous fumes were evolved, and flames appeared. No rearrangement could be detected, but deeply coloured solutions were formed, which gave tar, phenols, and nitrous acid on dilution. With less concentrated acid, the rearrangement took place, and in 16.1M-sulphuric acid over 95% of the theoretical yield of *o*- plus *p*-nitroaniline was isolated.

In summary, the product proportions do not vary greatly over a wide range of acidity and water activity, in spite of the presence of extensive side reactions at low acidities. This suggests that the mechanism is the same over the whole range; and the preponderance of

¹³ Banthorpe and Thomas, unpublished results.

¹⁴ Clarkson, Holden, and Malkin, *J.*, 1950, 1560.

¹⁵ Snyder, *J. Amer. Chem. Soc.*, 1962, **84**, 340.

the *ortho*-isomer further suggests an intramolecular pathway, for intermolecular rearrangements generally give *para*-products.

(4) *Attempts to Detect Intermediates*.—It was recently suggested⁹ that one pathway for nitroamine rearrangements involved an anilinium ion-radical and nitrogen dioxide. We have accordingly tried to detect radical or other intermediates.

Ascorbic acid, α -naphthol, or quinol, when added in equimolar or greater proportions, had little effect on the rate of rearrangement in the range of acidities permitting measurement; but they did appear, from determinations by colorimetry, to reduce the formation of nitroanilines to 80–90% of the values obtained in the absence of radical scavengers (although with little or no change in *ortho*:*para* ratio) (cf. Table 3). The situation is, however, too complex for these results to be attributed simply to the trapping of a radical intermediate, for all the additives are highly susceptible to attack by radicals, nitrous acid, and perhaps protonated nitroamine. An explanation is not possible without a knowledge of the nature of the coloured products formed by reaction of these additives with, for instance, nitrous acid, and in the absence of methods for separating these coloured products from the nitroanilines and the hitherto unidentified reaction products.*

TABLE 3.

Effect of additives on the rate of rearrangement and the optical density of the final reaction mixture.

[Substrate] $\sim 1.5 \times 10^{-4}M$; reactions in water at 25°.				
Additive	Molar ratio *	Acid	10^4k_1 (sec. ⁻¹)	Ratio of O.D. †
None	—	1.48M-HClO ₄	1.1	—
Ascorbic acid	1.0	„	1.1	0.83
Quinol	1.0	„	1.1	0.83
None	—	2.22M-HClO ₄	3.5	—
Ascorbic acid	1.0	„	3.3	0.87
„	2.2	„	3.4	0.85
„	5.1	„	3.3	0.80
α -Naphthol	1.2	„	3.4	0.88
„	2.2	„	3.4	0.89
<i>m</i> -Dinitrobenzene	1.0	„	3.5	0.98
„	2.0	„	3.4	0.99

* Moles of additive per mole of substrate. † The ratio of the optical density, at the isosbestic point, of the completely rearranged solution containing additive to that under similar conditions of the solution without additive.

More significant was the finding that *m*-dinitrobenzene, which has been found to be an efficient radical trap in other rearrangements¹⁶ and does not react with nitrous acid, had no effect on rate or products when present in equimolar or greater quantity. Also, a molar excess of α -naphthylamine completely suppressed the formation of rearrangement products in 3M-perchloric acid and gave a red solution which had an absorption spectrum identical with that of the coupling product of diazotised α -naphthylamine and aniline. When aniline was added under similar conditions, about 5% of benzenediazonium salt was detected by coupling with α -naphthol, but no coupling product was found in the rearranging solution. A small amount (*ca.* 1%) of emeraldine was also found.

These results are consistent with rearrangement accompanied by some fission to nitrous acid, which can be absorbed by azide, by aniline, or by the initially mentioned three additives with the formation of complex products. A readily diazotisable species such as α -naphthylamine can react, not only with nitrolysis products, but also with the protonated substrate to remove the stoichiometric equivalent amount of nitrous acid.

* The experiments with added azide detailed in section 3 involved a simple stoichiometric reaction followed by actual product isolation, and so were not beset with these difficulties.

¹⁶ Traynelis and Martello, *J. Amer. Chem. Soc.*, 1958, **80**, 6590; 1960, **82**, 2744.

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We have found no evidence for radicals in the range 1—18M-sulphuric acid by using electron spin resonance techniques: no signal was obtained even in the region in which brilliant colours appeared (see section 3). Also no polymerisation of added styrene, acrylonitrile, methyl methacrylate, or styrene-tristearin emulsion could be detected in the regions of acidity where such experiments could be carried out without causing extensive polymerisation due to the acid.

(5) *The Intramolecularity of the Reaction.*—The substrate was rearranged in the presence of nitric or nitrous acid labelled with ^{15}N ; the *ortho*- and *para*-isomers were separated and the ^{15}N contents compared with those of isotopically normal compounds (Table 4).

Whatever fragment, whether NO_2^+ , NO_2^- , NO_2 , NO^+ , or NO is formed on disproportionation, rapid equilibration with the tracer would have occurred under these conditions.^{17,18} As a large excess of the carrier containing 7.95% atoms excess of ^{15}N was used in each experiment, these results show that less than 3%, if any, of each isomer was formed intermolecularly.

This is the first demonstration of the intramolecularity of the rearrangement of a particular substrate over a wide range of reaction conditions.

(6) *Experiments with Deuterated N-Nitroanilines.*—The effect of *o*- and *p*-deuteration on rates and products was determined. For experimental convenience, the 2,3,5,6-tetra- and the 2,4,6-tri-deuterated substrates were employed, rather than those labelled solely in

TABLE 4.
 ^{15}N -Abundance in rearrangement products.

Acidity	Tracer as	^{15}N atoms % excess in <i>o</i> -isomer	^{15}N atoms % excess in <i>p</i> -isomer
75% w/w $\text{H}_2\text{SO}_4\text{-H}_2\text{O}$	KNO_3	<0.1	<0.1
37% w/w $\text{HClO}_4\text{-H}_2\text{O}$	HNO_3	<0.1	<0.1
Aq. M- HClO_4	KNO_2	<0.2	<0.2
Aq. 0.1M- H_2SO_4	KNO_2	<0.2	<0.2

the *ortho*- or *para*-position. This added complexity may introduce secondary isotope effects, but should not alter any conclusions concerning the occurrence of C-H fission in a kinetically significant step or at a branch point decisive for product formation. Results are shown in Table 5; each comparison of normal and deuterated compounds was done

TABLE 5.
Rates and products of normal and deuterated *N*-nitroaniline.

	2,3,5,6- D_4	Normal
Products, 75% aq. H_2SO_4 at -20°	95% <i>o</i> -isomer	95% <i>o</i> -isomer
Products, 37% aq. HClO_4 at 0°	68% <i>o</i> -isomer	72% <i>o</i> -isomer
k_1 , 3.24M- HClO_4 at 25°	$11.5 \times 10^{-3} \text{ sec.}^{-1}$	$11.5 \times 10^{-3} \text{ sec.}^{-1}$
	2,4,6- D_3	Normal
Products, 50% aq. HClO_4 at 0°	82% <i>o</i> -isomer	75% <i>o</i> -isomer
Products, 26% aq. HClO_4 at 0°	83% <i>o</i> -isomer	70% <i>o</i> -isomer
k_1 , 3.24M- HClO_4 at 25°	$11.7 \times 10^{-3} \text{ sec.}^{-1}$	$11.5 \times 10^{-3} \text{ sec.}^{-1}$

under identical conditions and the accuracy of the product analysis was about $\pm 1\%$ actual unit.

These results indicate (a) that deuteration where aromatic bonds have to be formed makes no noticeable difference to the rate of rearrangement, (b) that *ortho*-deuteration leads to more *para*-product, and that additional *para*-deuteration more than undoes this effect, so giving considerably less *para*-product, and (c) that the product isotope effect is most important at low acidities.

No *o*-deuterium effect on the products occurred at the highest acidity, but effects

¹⁷ Stedman, Ph.D. Thesis, London, 1955.

¹⁸ Bunton *et al.*, *J.*, 1953, 2653; 1958, 2440.

(k_H/k_D) of 1.2 for *ortho*-deuteration and 1.8 and 2.5 for *para*-deuteration (all ± 0.1) were obtained at the lower acidities. The last two values were calculated by assuming that an *ortho*-deuterium effect as obtained in 37% aqueous perchloric acid occurred to the same extent in these *ortho*- and *para*-deuterated species.

The isotope effect of 1.2 may be a secondary effect due to different susceptibilities to hyperconjugation, or to hybridisation changes in the normal and deuterated molecules, or it may be due to ponderal effects.¹⁹ However, even though secondary effects caused by hyperconjugation should be enhanced in more aqueous media,²⁰ the other values seem too large to be attributable to this. It seems more likely that these isotope effects arise because the rate expression for product formation is a function of rate constants referring to steps in which C-H bonds are broken.

(7) *Discussion*.—Several conclusions have already been reached. The initial step of the reaction is a pre-equilibrium proton-transfer to form an intermediate, which probably breaks down without solvent intervention. There is no evidence for radical reactions or for appreciable disproportionation to nitrous acid; and such of the latter as does occur definitely forms nitrite rather than nitrate ion. The product studies suggest that a single mechanism applies over the whole range of available acidities, and the tracer work indicates that this is intramolecular. Finally, the loss of aromatically bonded hydrogen is kinetically insignificant, but there is some isotopically induced discrimination between pathways leading to *ortho*- and *para*-positions.

As there is no evidence for intermediates that would restrict the kinetic freedom of any product of disproportion to nitrous acid, the simplest mechanism that can be written requires migration, even to the *para*-position, to occur by synchronous reactions involving conventionally bonded species.

Recent Theories of Nitroamine Rearrangements.—Two theories of the mechanism of nitroamine rearrangements have been proposed recently. White and his co-workers⁹ found that, although the rate of rearrangement of *N*-methyl-*N*-nitroaniline in 0.1*N*-hydrochloric acid at 40° was unaffected by added iodide ion, quinol, or α -naphthol, yet the recovery of rearrangement products was drastically reduced by these additives, and much *N*-methylaniline and nitrous acid was then formed. These observations were held to support a mechanism involving ion- and radical-pairs,* although the products of radical decomposition were not detected.^{21,22} White's reaction conditions were far removed from ours, and unlike us he found no *ortho*-deuterium isotope effect, but he noticed large quantities of disproportionation products. Obviously, any mechanistic conclusions from such experiments need not apply to our substrate in our acidity ranges. Also, there is some ambiguity about White's experiments. First, the low acid concentration but high temperature seem ideal for the appearance of a thermal rearrangement as a component of the reaction, such as we have found to occur for *N*-methyl-*N*-nitronaphthylamine,¹³ but this possibility was not checked. Secondly, it is not clear whether *C*-nitrosation and oxidation to a nitroamine, either direct or by *N*-nitrosation and Fischer-Hepp rearrangement, could have occurred. This pathway to products may account for the effect of the scavengers, and also for the intermolecular component detected under similar conditions⁶ (conditions where no attempt was made to detect or to destroy any concurrently formed nitrous acid). In the last context it is noteworthy that an earlier study⁵ by the same labelling technique had shown the acid-promoted rearrangement of *N*-nitroaniline to be completely intramolecular. But here the conditions (ethereal hydrochloric acid) would have disfavoured disproportionation, and direct nitrosation or Fischer-Hepp migration could not have occurred. Finally, the scavengers that were used all readily react with

* As formulated, the mechanism involved a rate-determining interconversion between two canonical forms of a resonance hybrid.

¹⁹ Dewar, "Hyperconjugation," Ronald, New York, 1962, p. 131.

²⁰ Shiner, *J. Amer. Chem. Soc.*, 1954, **76**, 1603.

²¹ Barnes and Hickinbotham, *J.*, 1961, 2616.

²² Hollingsworth, *J.*, 1959, 2420.

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nitrous acid or nitryl chloride, and so any phenomena observed in the presence of scavengers are not unique evidence for radical processes.

White did not develop a mechanism for the *para*-migration beyond vague speculation about a radical pair. However, other radical pairs exist only below -80° , and are totally different in electronic structure to the type that must be postulated for nitroamine rearrangements.^{23,24} Such a radical pair would be much more likely to occur in certain benzidine rearrangements in which monoprotonated substrates react, but all the available evidence is against such species even in these situations.⁷

Another mechanism has been proposed by Dewar²⁵ for these and for most other types of intramolecular rearrangements. The protonated nitroamine is supposed to undergo heterolysis to a nitronium ion, which bonds to the π -electrons and undergoes internal migration. Such π -complexes have also been postulated in elimination, addition, and aromatic substitution, but there is little, if any, evidence for their participation in any of these reactions, and the doubtful basis of the theory is often overlooked.²⁶ Further, the predictions of the π -complex theory as applied to the benzidine rearrangement have recently been decisively disproved,⁷ and the observation that a series of *para*-substituted *N*-nitroanilines obeys an excellent Hammett $\sigma^+ - \rho$ relation⁹ rules out heterolysis in the direction required by this theory*—at least under the particular set of conditions for which the kinetics were studied.

Our present results are also incompatible with these theories. Thus we and others^{2,4,9} have found no nitrate ion, but only nitrite ion, amongst the disproportionation products, whereas Dewar's theory would require all the disproportionation to yield nitrate and White's mechanism would require significant proportions of nitrate to accompany the nitrite (for any solvolysis of nitrogen dioxide would give equimolar amounts of these ions). Secondly, we have found product isotope effects, whereas Dewar's mechanism would almost certainly require a practically irreversible conversion of a π -complex into a σ -complex before the aromatic hydrogen was lost, and so no such effects would be expected.

As we shall discuss later, nitroamine rearrangements may not involve the conventional Wheland-type intermediates. However, the transition states formulated by White as leading to products *are* identical with those for *ortho*- and *para*-nitration of aniline by nitronium ion, and so any isotope effects should be identical for the two reactions. Unfortunately, isotope studies of the latter reaction have not been carried out, but by analogy with other nitrations no isotope effect would be expected. Likewise, no product change on *ortho*- or *para*-deuteration would be expected for any mechanism that involved a competition between different routes leading to *ortho*- and *para*-products passing through Wheland-type intermediates similar to those in nitration.

Thus, neither of the above schemes is wholly acceptable, and the most probable alternative seems to be a mechanism in which the migrating species is held to the aromatic fragment by covalent or electrostatic bonds, and the migrations involve synchronous bond-breaking and bond-forming. There are formidable stereochemical difficulties to be faced on any such route. Internuclear distances between the reacting atoms as calculated from Dreiding-Büchi models are shown in Fig. 1, and, if we exclude mechanisms involving ion-pairs (which we shall discuss shortly), direct *para*-migration seems out of the question (Fig. 1a). Although N-N fission and synchronous bonding to form an *ortho*-linked nitro- or nitrated intermediate is stereochemically possible, only the further reaction of a nitrite intermediate to the *para*-position seems likely (cf. Fig. 1b and d).

The "Cartwheel" Mechanism.—One of us previously suggested¹ that the reaction

* The initial heterolysis is probably rate-determining, but these results are also incompatible with Dewar's theory if the conversion of the π -complex into a σ -complex, or the final loss of aromatic hydrogen is rate-determining.

²³ Murrell and Hausner, *J. Chem. Phys.*, 1957, **27**, 500.

²⁴ Lord and Porter, *J.*, 1961, **3540**.

²⁵ Dewar in de Mayo's "Molecular Rearrangements," Academic Press, New York, 1963, Vol. I, p. 295.

²⁶ Coulson and Dewar, *Discuss. Faraday Soc.*, 1947, **2**, 54.

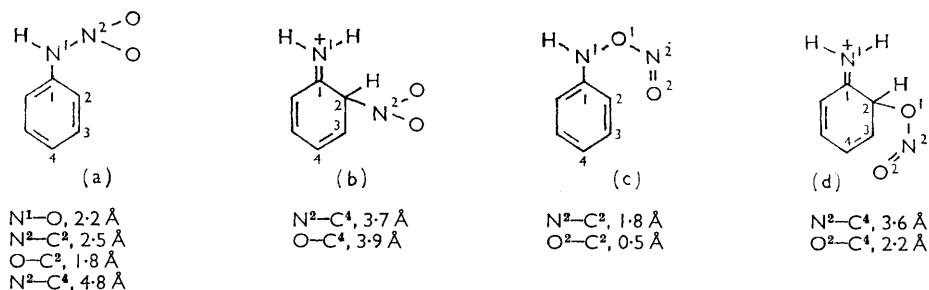


Fig. 1. Calculated internuclear distances.

involves initial isomerisation to an *N*-nitrite, which then forms the *para*-isomer by an *ortho*-migration through a series of cyclic, strainless transition states (cf. Fig. 2). (The details of the *C*-nitrite to *C*-nitro change will be considered shortly.) This mechanism provides a feasible route for *para*-migration (cf. Figs. 1c and d), but the main difficulty of the original

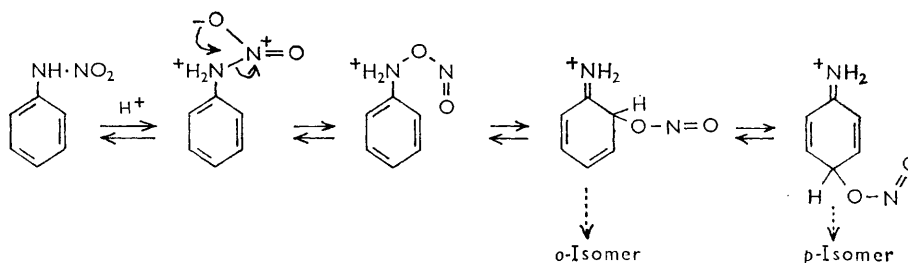


Fig. 2. The "cartwheel" mechanism.

scheme is to justify the initial isomerisation. There are many analogies for the subsequent *ortho*-migration in aromatic rearrangements²⁷ and nitrations,^{28,29} and for the *para*-migration in the Claisen rearrangement,³⁰ but none for the initial step. It seems reasonable that the protonated nitro-form should rearrange to an *N*-nitrite; this could minimise adjacent charge repulsion and form a system that, on loss of the *N*-bonded proton, would be capable of quite extended conjugation; but a nitrite form of the unprotonated substrate has never been characterised, although spectral and chemical data adduced in favour of an *aci*-form of *N*-nitroaniline³¹ may well refer to a nitrito-form. Thus, although we do not exclude the *N*-nitrite from our modified reaction scheme, we think that a direct *N*-nitro- to *o*-*C*-nitrite migration may occur and be followed by a "cartwheel" to the *para*-position.

Dewar²⁵ has objected that nitrite intermediates would be hydrolysed to nitrous acid, nitrophenols, and phenylhydroxylamines under the reaction conditions (and the last-mentioned would immediately decompose to tars³²); actually, a few units percent of these products can be isolated in our example and considerably more in others.² His argument depends, however, on analogy with the reactions of alkyl nitrites, for no aromatic nitrite or nitrito-amine is known. The differences in the acid-catalysed decompositions of *N*-nitroalkyl- and -aryl-amines³³ show how dangerous such comparisons can be, and the intermediates in the "cartwheel" mechanism would be expected to behave quite differently

²⁷ Huisgen *et al.*, *Chem. Ber.*, 1959, **92**, 3224; 1960, **93**, 363; *Annalen*, 1960, **630**, 138.

²⁸ Norman and Radda, *J.*, 1961, 3610.

²⁹ Podkowska and Tarnawski, *Monatsh.*, 1959, **90**, 179.

³⁰ Schmidt *et al.*, *Helv. Chim. Acta*, 1953, **36**, 489; 1954, **37**, 1908.

³¹ Salyamov *et al.*, *Sbornik Statei obschei Khim.*, 1953, **2**, 1315 (*Chem. Abs.*, 1955, **49**, 4554).

³² Heller, Hughes, and Ingold, *Nature*, 1951, **168**, 909.

³³ Lamberton, *Quart. Rev.*, 1951, **5**, 75.

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from alkyl nitrites. In particular, protonation and subsequent fission of the C-nitrite intermediates should not be particularly easy, because of positive-charge repulsion, and because these intermediates would have a very pressing alternative mode of decomposition to form rearrangement products. One can no more expect the chemistry of these compounds and their alkyl analogues to be similar than one can expect a similar situation for alkane- and arene-diazonium ions.

We are at present carrying out experiments to test the occurrence of nitrite intermediates. Meanwhile, if we accept the "cartwheel" mechanism as a working hypothesis we can interpret our and others' results in a consistent manner. We now discuss these results on the basis of a mechanism involving an N-nitrite, but the crux of the scheme is the occurrence of C-nitrites, and the former intermediate can be by-passed by a direct N-nitro to C-nitrite rearrangement without requiring more than minor adjustments.

(a) *Stoichiometry.* It has generally been assumed (except by White⁹) that disproportionation leads to formation of free amine and nitronium ion, the latter forming nitric acid in all except strong acids. As previously mentioned, there is compelling evidence that disproportionation leads to nitrite, but no nitrate, ion. Thus, free nitrous acid is often detected, especially at elevated temperatures and when 2,4,6-substituted nitroamines are studied;² media such as acetic acid readily capture nitrous acid from the substrate;² benzoquinone and imines derived from the counter-dication have been isolated² and no nitrate has ever been detected. Cross-nitration of reaction additives⁴ could result from nitrosation, and substrates such as 4-nitro- and 2,4-dinitro-phenylnitroamine, in which a split to the nitronium ion would be especially favoured, rearrange intramolecularly with no detectable disproportionation to nitrous acid,³ although the 2,4,6-trinitro-derivative may split in this way.^{34,35}

As disproportionation accompanies rearrangement, it is likely that both processes result from bond heterolysis in the same direction, and this is supported by recent kinetic studies.⁹ When the bond formation necessary for rearrangement is uncoupled from the initial heterolysis, nitrite ion is formed. This direction of fission is consistent with the participation of an N-nitrite, for an N-nitro-compound (which the kinetics show must react in a protonated form) would have to split so that the bond electrons moved away from a highly localised positive pole; fission to a nitronium ion seems more likely. On the other hand, a protonated N-nitrite, formed in the rate-determining step, could lose a proton and undergo heterolysis so that the electrons moved towards the more electronegative atom. However, as a referee has pointed out, fission to nitrous acid would also occur if protonation were on the nitro-oxygen rather than on the amino-nitrogen atom; and such fission could compete with direct rearrangement from the O-protonated N-nitro-compound to the C-nitrito-species.

At low acidities, the N-nitrite, probably unprotonated, would rearrange but would suffer severe attack by the solvent to give nitrous acid, tars, and nitrophenols, and the nitrous acid could react with unchanged substrate to give complex products. Added scavengers could absorb nitrous acid, and reducing agents could convert the di- or mono-anilinium ions into amines or anilino-radicals, which could then react to form emeraldine-like products.^{9,36} At higher acidities, the N-nitrite would be protonated, and attack by protons on the nitrito-oxygen atom would be inhibited. A more concerted rearrangement would probably occur, which would give the solvent molecules (whose activity would now be low) little chance to intervene. Side reactions would thus become less important with increasing acidity but, at higher acidities, added nitrate, nitrite (as NO_2^+ or NO^+), or chloride ion could capture part of the rearranging entity.^{1,4} At the highest acidities (~18M-sulphuric acid), no base is readily available to complete the rearrangement by

³¹ Glazer, Hughes, Ingold, James, Jones, and Roberts, *J.*, 1950, 2657.

³⁵ Mitra and Swinivasan, *Analyst*, 1945, **70**, 478.

³⁶ Mizoguchi and Adams, *J. Amer. Chem. Soc.*, 1962, **84**, 2085; *J. Phys. Chem.*, 1963, **67**, 862.

deprotonation, and much disproportionation would occur and produce coloured solutions. On dilution, much tar and complex products would be formed by attack of solvent on the disproportionation products and by reactions between these products.

The assumption that our nitrite-intermediates are susceptible to solvent attack only at low acidities is not particularly damaging to our theory, as a similar assumption must be made for the intermediates in the radical, π -complex, or any other theory.

(b) *Detailed mechanism.* The "cartwheel" mechanism overcomes the stereochemical difficulties of *para*-migration by providing a discrete *o*-bonded intermediate. No kinetic isotope effect would occur if the energy barrier between protonated *N*-nitro- and *N*-nitrite forms, or between the latter and any *C*-nitrite form, were higher than that between the two *C*-nitrites and higher than the barrier for proton loss; but the branching point in product determination (see Fig. 2) permits a product isotope effect.

The Wheland *o*-nitrito-intermediate would have a transient existence. The nitrite group could migrate to the *para*-position (Fig. 1d); and there is some possibility of decomposition to an aromatic nitrite and an aminophenol, but the predominant reaction would lead to *o*-nitroaniline.

There would be a great tendency to aromatisation, and the incipient aniline molecule would be presented with an almost unsolvated developing electrophile in close contact, in a situation quite different from that obtaining in nitrating mixtures or even in nitration with nitronium salts in non-aqueous media.³⁷ Direct electrophilic ejection of hydrogen would be likely without the formality of forming a σ -nitro-linked Wheland intermediate for, as pointed out by Eyring,³⁸ an intermediate occupying a shallow potential-energy hollow below the highest energy barrier may be by-passed in a highly exothermic process in the precipitous run-down to products. This mechanism would lead to a product isotope effect on *ortho*- or *para*-deuteration, and the size of the effect would depend on the amount of proton transfer from the aromatic ring to the accepting base. As the carbon-hydrogen bond would only be incipiently broken in the transition state of such an exothermic reaction,³⁹ only small isotope effects would be observed.⁴⁰ However, at high acidities (*e.g.*, 16*M*-sulphuric acid) the displacement of a proton would not be easy, owing to the lack of available bases, and a σ -nitro-linked Wheland intermediate would be formed. This second Wheland intermediate would be more stable than the first, and recent nitration studies⁴¹ have indicated that a reverse nitro-nitrito-change is unlikely; thus no product isotope effect on nitration would occur.

The only remaining experimental finding to accommodate in our scheme is the increase in the proportion of *para*-isomer at low acidities. We have shown this to be a real effect and not to be due to a selective destruction of the *ortho*-isomer by nitrous acid. At higher acidities, all proton losses are retarded, as explained above, but the greater isotope effect of *para*-deuteration than of *ortho*-deuteration in displacing the product proportions away from the deuterated position strongly suggests that proton loss is more difficult from *para*- than from *ortho*-positions. In that case, the *para*-position will be discriminated against when the proton-accepting power of the medium is diminished. This will cause the *ortho*-isomer to predominate at high acidities, and the proportion of the *para*-isomer to increase as the acidity is reduced.

Other Mechanisms.—Direct migration from the side chain to the *para*-position involving a covalently bonded species seems out of the question (see Fig. 1a), even if the geometrical problem is alleviated somewhat by a rehybridisation at C¹, such as has been suggested to overcome a similar stereochemical difficulty in the benzidine rearrangement.⁴² But the

³⁷ Olah and Flood, *J. Amer. Chem. Soc.*, 1962, **84**, 1688, 1695.

³⁸ Eyring, Laidler, and Glasstone, "Theory of Rate Processes," McGraw-Hill, New York, 1941, p. 100.

³⁹ Hammond, *J. Amer. Chem. Soc.*, 1955, **77**, 334.

⁴⁰ Westheimer, *Chem. Rev.*, 1961, **61**, 265.

⁴¹ Zollinger and Suhr, *Helv. Chim. Acta*, 1961, **44**, 1011.

⁴² Hammick and Mason, *J.*, 1946, 658.

migration is feasible if the migrating group is a bidentate quasi-ion held to the aromatic fragment by largely electrostatic bonds. Such a species, orientated for *para*-migration and derived from the protonated *N*-nitrite, is represented in Fig. 3.

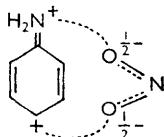


Fig. 3.

This scheme has similarities to a mechanism proposed for benzidine rearrangements,⁷ and the aromatic fragment resembles a reasonably stable intermediate recently identified in the anodic oxidation of dimethylaniline.⁴³ As explained before,⁷ the positive charge on the dication would be mainly anchored on the nitrogen and the *para*-carbon atom, but appreciable charge would also be present at the *ortho*-positions in the vicinity of the migrating species. A synchronous electrophilic substitution would give a highly unstable aromatic nitrite, and an *ortho*- or *para*-linked Wheland nitrito-complex would probably be formed which would decompose by the "cartwheel" mechanism.

Such a mechanism can accommodate the observed isotope effects, but we think it would require much greater solvent interaction, especially at low acidities, than actually occurs with our substrate. Thus the migrating ion would have to steer well clear of the aromatic fragment to circumnavigate the π -shell, and any direct *para*-migration would not be expected to compete effectively with *ortho*-migration. In particular, up to 30% of the *para*-product would not be expected without much accompanying formation of nitrous acid.

An *N*-methyl group could favour this ion-pair mechanism, and it may be significant that White *et al.*⁹ found much disproportionation to accompany a large proportion of *para*-isomer on rearranging *N*-methyl-*N*-nitronitroaniline at low acidities; but they also found, in contrast to the situation with the non-methylated homologue, that there was no isotope effect on the products.

Conclusion.—We have argued, in marshalling evidence for the "cartwheel" mechanism, that the nature of the disproportionation product throws light on the direction of the initial heterolysis in the rearrangement. The alternative, that two distinct processes occur—disproportionation and rearrangement—which involve bond fission in opposite directions, seems less likely. One cannot argue that the *aci*-form reacts in the former and the *N*-protonated nitro-form in the latter process, for disproportionation occurs with *N*-methylated substrates^{9,13} where no *aci*-form is possible. Also, any rearrangement involving reaction between a nitronium ion and an amine would not only be inconsistent with the kinetics⁹ but would also have to be assumed to take place in a solvent cage with no interference by water or other substrate molecules; and, as the reaction would presumably occur on every encounter, a vast predominance of *ortho*-isomer and perhaps some *meta*-isomer would be expected, especially at low acidities.

We think that the "cartwheel" mechanism, perhaps incorporating an initial *N*-nitro to *N*-nitrite conversion, is consistent with all that is known about *N*-nitroaniline and can accommodate all the facts about other nitroamines. We are at present studying more complicated systems and are particularly concerned to obtain evidence for nitrite intermediates.

EXPERIMENTAL

Preparations.—*N*-Nitroaniline. Small pieces of potassium (12 g.) were dissolved in ethanol (54 ml.) under nitrogen, then more metal (5 g.), dry ether (60 ml.), and aniline (36 g.) were added and the whole was refluxed for 8 hr. On slow addition of ethyl nitrate (31 ml.) to the cold stirred solution, the potassium salt of *N*-nitroaniline was precipitated (60% yield). The free nitroamine (30%) was obtained by slightly acidifying an aqueous solution of this salt with 10% hydrochloric acid at 0° and extracting it with ether; crystallised from ligroin (b. p. 110–120°), it had m. p. 44°. Bamberger's method⁴⁴ of oxidising potassium benzenediazotate was found to be very unsatisfactory.

⁴³ Mizoguchi and Adams, *J. Amer. Chem. Soc.*, 1962, **84**, 2065.

⁴⁴ Bamberger, *Ber.*, 1893, **26**, 472; 1894, **27**, 363.

2,3,5,6-Tetradeuterio-N-nitroaniline. 2,3,5,6-Tetradeuterioaniline, prepared as previously described,⁴⁵ was used in the above preparation. The deuterium content of the final nitroamine was measured by mass spectrometry, and the substrate and the rearrangement products were both examined. The former, owing to its thermal instability (explodes at $>96^\circ$) was introduced into a Metro-Vick MS2 instrument at 80° , and the latter at 300° . Blends of the normal and deuterated compounds were made for calibration, and the mass spectra were recorded at 12, 16, and 70 eV; peaks heights monoisotopic with respect to carbon were measured. The results from both types of compound showed that the *N*-nitroaniline contained 84% of *o*-deuterium, 100% of *m*-deuterium, and no *p*-deuterium (all $\pm 2\%$ actual units).

2,4,6-Trideuterio-N-nitroaniline. Aniline hydrochloride (9 g.) in 99.8% D_2O (60 ml.) was kept in a sealed tube at 100° for 48 hr. Under these conditions, all *ortho*- and *para*-positions became almost completely deuterated.⁴⁶ The amine was then converted into the nitroaniline. Combustion analysis of the *o*- and *p*-nitroaniline formed by rearrangement, and infrared determination of D_2O indicated that $>99\%$ exchange had occurred at the *ortho*- and *para*-positions.

Products of Rearrangement.—*N*-Nitroaniline (0.5 g.) was added to the required acid (ca. 30 ml.) at 0° or occasionally (e.g., for 75% w/w sulphuric acid–water) at -20° and kept overnight. For the more dilute acids, the nitroaniline was often added in ethanolic solution; it was checked that this co-solvent did not affect the product proportions. The solutions were then diluted two-fold, cautiously made alkaline with sodium carbonate solution at 0° , and shaken with chloroform. The solvent was removed from the dried extract, and the nitroanilines were distilled at 0.1 mm. from any tar; it was checked that no other product distilled under these conditions. Control experiments shows: that *ortho*:*para* ratios were repeatable to $\pm 1\%$ (actual value) by this technique; that any loss of the amino-group with the formation of nitrophenol during the neutralisation, such as readily occurs under similar conditions in the naphthalene series,¹³ did not intrude; and that no denitration or interconversion of isomers took place.

The proportions of the extracted nitroanilines were measured as follows. A solution of known concentration was made up and the optical density was measured at a given wavelength with a Unicam S.P. 500 spectrophotometer. As spectroscopy and chromatography showed that no *meta*-isomer or other component was present, these measurements allowed calculation of the product proportions. Each analysis was calculated for several wavelengths over the range 330–400 $m\mu$ and the method was found to reproduce values within $\pm 1\%$ for a standard mixture. Some spectral results are given in Table 6.

TABLE 6.
Spectrophotometric results for *o*- and *p*-nitroanilines.

Solvent	$10^3\epsilon$ at 400 $m\mu$		$10^3\epsilon$ at isosbestic point
	<i>o</i> -Isomer	<i>p</i> -Isomer	
H ₂ O	4.15	11.67	4.00 at 431 $m\mu$
EtOH	5.47	9.92	5.40 at 412 $m\mu$

Nitrophenols and various unidentified products were obtained in yields of up to a few per cent from the alkaline layer.

Some analyses were carried out by column chromatography on alumina;⁴⁷ here, the reaction mixture after neutralisation and extraction was used directly.

The deuterated products were analysed by the spectrophotometric method, for it is known that the substitution of up to four deuterium atoms in a benzene ring does not affect the extinction coefficient at a given wavelength, as measured for the protium analogue.⁴⁵ It was checked that the deuterated substrates did not undergo exchange before rearrangement; thus, isotopically normal nitroaniline was rearranged in 75% D_2SO_4 - D_2O and gave products which, after the amino-hydrogen atoms had been equilibrated by dissolution in and recovery from a large excess of ethanol, contained no deuterium detectable by infrared analysis.

Tracer Experiments.—A typical run was as follows. *N*-Nitroaniline (0.2 g.) was rearranged in 37% perchloric acid (100 ml.) in the presence of 6.29M-nitric acid (5 ml.) which was labelled with ^{15}N in 7.95% atoms excess. The products were separated as usual and the chloroform

⁴⁵ Banthorpe and Hughes, *J.*, 1962, 3308.

⁴⁶ Best and Wilson, *J.*, 1936, 239.

⁴⁷ Larsen and Henry, *Chem. and Ind.*, 1954, 45.

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extract was reduced to about 10 ml. and chromatographed on alumina with a 3 : 7 mixture of benzene and light petroleum (b. p. 40—60°). The column was extruded and cut as soon as the bands had separated, and the products were eluted, recrystallised from water, and examined for ^{15}N content by mass spectrometry. The amines were fed into the mass spectrometer at 300°, and the prominent peak at 138 due to the molecule ion $\text{C}_6\text{H}_6\text{N}_2\text{O}_2^+$ and the smaller peak at 139 (an unresolved multiplet due to molecules containing one atom of ^2H , ^{13}C , ^{15}N , or ^{17}O) were measured. The ratio of the peak heights at 139 and 138 were 0.076 or 0.077 ± 0.001 in all cases, and this was within the experimental error for the values obtained with isotopically normal compounds. It was calculated that the samples contained <0.2% of a species $\text{C}_6\text{H}_6^{14}\text{N}^{15}\text{NO}_2$ in excess of the natural abundance, and this meant that less than 3% of each product could have incorporated ^{15}N .

Kinetics.—These were studied in aqueous perchloric and sulphuric acid at 25°. Each aliquot portion was made alkaline with sodium hydroxide solution and the colour intensity measured at 400 m μ . All runs gave good first-order rate constants in the substrate, the reproducibility within and between runs being ca. 1—2%. A typical run was

Time (min.) ...	0	5	13	25	40	50	60	75	∞
Optical density ...	0.000	0.036	0.074	0.120	0.162	0.178	0.199	0.212	0.249

A logarithmic plot gave $k_1 (4.41 \pm 0.10) \times 10^{-4} \text{ sec.}^{-1}$. The runs with added scavengers usually contained 1-, 2-, or 5-fold molar excess of the additive.

Other Experiments.—Nitrate and nitrite ion were estimated by conventional colorimetric and polarographic methods; emeraldine, nitrobenzene, and the other side products were isolated by chromatography on alumina and characterised by infrared spectroscopy. Attempts to detect free aniline and benzidine-type products were made by paper chromatography.⁴⁸

Tests for radicals were made by the addition of 10% by volume of styrene, methyl methacrylate, acrylonitrile, and styrene-tristearin emulsion. Control experiments were carried out to guard against polymerisation by the catalysing acid; at concentrations above 3—5M-acid, such polymerisation was extensive.

Electron-spin-resonance measurements were carried out on as concentrated solutions of the substrate as possible in 18-, 9-, and 1M-sulphuric acid. Solutions were made up at 0° in capillary cells and were immediately frozen in liquid nitrogen and degassed. They were then examined in the spectrometer over periods of up to 30 min. while being cooled at 0°.

We are very grateful to Drs. A. Quayle and R. S. Airs of Shell Research (Thornton Research Centre) and to Dr. R. Reed of Glasgow University, who carried out the deuterium and ^{15}N analyses; to Dr. J. Pannell (Imperial Chemical Industries Limited, Plastics Division), who measured the electron spin resonance spectra; to Mr. J. A. Thomas, who made the polarographic and certain other measurements; to Professor Sir Christopher Ingold, Dr. J. H. Ridd, and Mr. J. A. Thomas for many stimulating discussions; and to the Directorate of Chemical Science, United States Air Force Office of Scientific Research, for providing a Fellowship to D. L. H. W.

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[Received, April 28th, 1964.]

⁴⁸ Vesera, Petranek, and Gasparic, *Coll. Czech. Chem. Comm.*, 1957, **22**, 1603.