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Reactions of Organic Compounds with Dissociation of N-N Bonds

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Reactions involving the dissociation of single N-N bonds which have been carried out during the last decade and which are important for organic chemistry are surveyed. New data on the reductive cleavage of such bonds, various rearrangements, N-N bond dissociation reactions with simultaneous *N*-alkylation, and thermal, electrochemical, and photochemical processes are examined. Attention is concentrated on fundamentally new reactions, on studies of the reaction mechanisms, and on the development of methods extending the preparative scope of organic synthesis.
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I. INTRODUCTION

Reactions proceeding with dissociation of N–N bonds in both cyclic and acyclic compounds occupy a major place in organic chemistry. Owing to the repulsion between the *p* orbitals of neighbouring nitrogen atoms, the length of a single N–N bond (1.40 nm) exceeds the sum of the radii of the two nitrogen atoms ($0.53 \times 2 = 1.06$ nm). A characteristic feature of this bond is its very low dissociation energy (37 kcal mol^{-1}) compared with other single bonds most frequently encountered in organic compounds (for example, the energy is 80 kcal mol^{-1} for the C–C bond, 66 kcal mol^{-1} for the C–N bond, and 64 kcal mol^{-1} for the S–S bond).

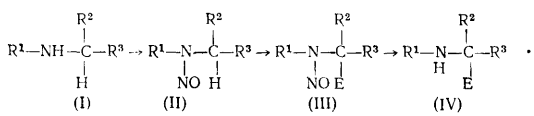
The above features of the N–N bond are responsible, under conditions where there is a possibility of competing reactions, for its preferential dissociation compared with the dissociation of the C–C or C–N bonds. This entails the formation of either the corresponding amino-derivative, or unstable products with an electron sextet at the nitrogen atom of the type of nitrenes, which are stabilised by further addition reactions, rearrangements, etc., or unstable free radicals, which recombine or undergo other radical processes ensuring the stabilisation of the molecule, are generated.

In our earlier review[1] an attempt was made for the first time to give a systematic account of the extensive literature data on the methods for the dissociation of single N–N bonds in organic compounds. The present review describes the advances during the last decade in the studies on organic compounds involving the dissociation of N–N bonds. Attention is concentrated on the examination of fundamentally new reactions, new studies on reaction mechanisms, and on the search for fundamentally new ways of employing processes of this type in preparative organic chemistry rather than on numerous new applications of compounds described previously.

II. REDUCTIVE CLEAVAGE OF N–N BONDS

The hydrogenolysis of N–N bonds is one of the commonest methods for the conversion of various azines, azides, hydrazines, and their derivatives into the corresponding amines. The methods for the reductive cleavage of N–N bonds published up to 1972 have been examined in detail in the authors' previous review[1] as well as other reviews.[2-6]

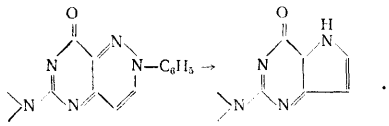
A new general method for the introduction of various substituents at the C(1) atom in secondary amines (I), based on their nitrosation, treatment of the nitroso-derivatives (II) with powerful bases and electrophiles, and reductive cleavage of the N–N bond in the nitrosoamine (III) in order to remove the nitroso-group, has been developed during the last decade:[7]



The last stage of the synthesis of compound (IV) is effected on the basis of a specially developed method for the reductive denitrosation of compound (III) with hydrogen in the presence of small amounts of Raney nickel.[8] This method proved to be suitable for compounds which are unstable in acid media, the other functional groups present in the substance (apart from the readily reducible olefinic and β-keto-groups), being unaffected under these conditions, which is the reason for its significant advantages over the earlier method for the denitrosation of amines with cleavage of the N–N bond in acid media.[9]

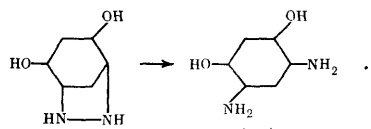
A method for the hydrogenolysis of the N–N bond in hydrazobenzene with formation of aniline via hydrogen transfer from 2-propanol to hydrazobenzene, catalysed by the triphenylphosphine complexes of rhodium and ruthenium, was published during the same period.[10]

By analogy with the other methods for the reductive cleavage of the N–N bond in pyridazine compounds indicated in the earlier review,[1] which lead to ring contraction, new syntheses have been developed for 5*H*-pyrrolo[3,2-*g*]-pyrimidines (V).[11] They include a stage involving the reduction of pyrimido[5,4-*c*]pyridazines (V) in the presence of a nickel or palladium catalyst.[11] The reductive opening of the pyridazine ring with dissociation of the N–N bond and the subsequent closure of a five-membered ring, the 4,6-diazaindole system (VI), are then observed:



(V) (VI)

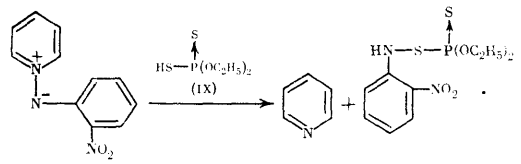
The catalytic reductive cleavage of both exocyclic[12] and endocyclic[13] N–N bonds in the synthesis of aminocyclitols (VII) has acquired considerable importance:



(VII)

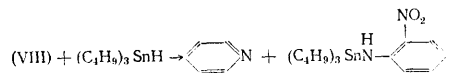
In view of the increasing importance of the problem of the protection of the environment, a study[14] in which a general method was proposed whereby various hydrazine compounds, including substances with a carcinogenic activity, can be made harmless by the reductive cleavage of their N–N bond with conversion into the corresponding less dangerous amino-derivatives, has attracted special attention.

Reduction with dissociation of this bond by a nucleophile, namely diethyl phosphinodithioic acid (IX), has been described for a compound with a semipolar N–N bond of the N-iminopyridinium type, namely the betaine (VIII):[15]

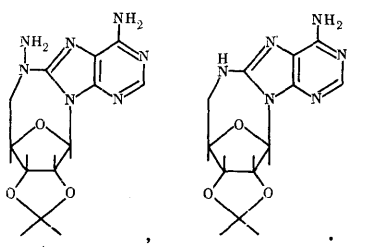


(VIII)

The same type of reaction takes place on treatment of compound (VIII) with tributyltin hydride[16] in the presence of αα′-azobisisobutyronitrile and is believed to be of the radical type:



In contrast to the reactions involving the reductive cleavage of N–N bonds described above, the oxidative cleavage of such bonds is also known and can be illustrated in relation to the deamination of the *N*-amino-derivatives (X) to give compound (XI) by oxidants such as iodine pentoxide, lead tetra-acetate, potassium permanganate, and sodium metaperiodate:[17]



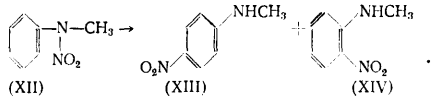
(X) (XI)

The deamination of 1,1-disubstituted aromatic hydrazines with the aid of nitrous acid, which apparently proceeds via *N*-diazonium salts, has also been studied in detail in recent years.[18]

III. REARRANGEMENTS INVOLVING THE DISSOCIATION OF N–N BONDS

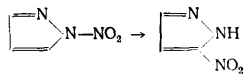
In addition to the sextet rearrangements of the type of the Curtius and Schmidt reactions and nitrile and various aryl-hydrazone rearrangements described in a previous review, publications dealing with new types of reactions, involving the cleavage of the N–N bond, have appeared during the last decade. At the same time, some of the reactions known previously not only came to be used more widely on a preparative scale but also have been the subject of more detailed theoretical and applied research.

For the acid-catalysed nitroamine rearrangement involving *N*-methyl-*N*-nitroaniline (XII), processes occurring in the presence of hydroquinone, which rules out an intermolecular reaction mechanism, were investigated, and it was shown that the yield of the *p*-nitro-isomer (XIII) relative to the *o*-nitro-amino-compound (XIV) increases appreciably with increase of the viscosity of the solution. According to the authors, this indicates the involvement of solvent molecules in the nitro-group migration processes:[19]



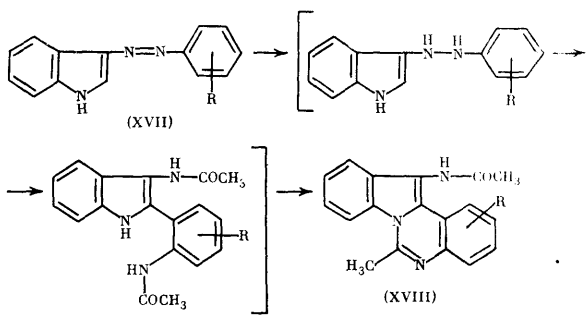
(XII) (XIII) (XIV)

The dissociation of the N–N bond accompanied by the rearrangement of the nitroamine type on thermolysis of 1-nitropyrazole (XV) to give 5-nitropyrazole (XV) and in other analogous reactions has also been described:[20]



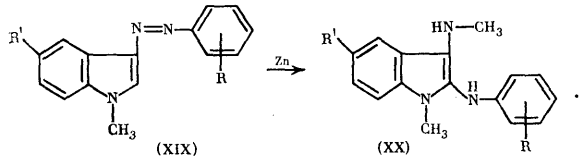
(XV) (XVI)

Vigorous studies on the mechanism of the benzidine rearrangement have continued.[21–27] When 3-arylozoindoles (XVII) were reduced with zinc in acetic acid in the presence of acetic anhydride and sodium acetate, a rearrangement of the *o*-benzidine type, proceeding with dissociation of the N–N bond and the formation, as a result of subsequent *N*-acylation and cyclisation, of derivatives of indolo[1,2-*c*]-quinazoline (XVIII) was observed:



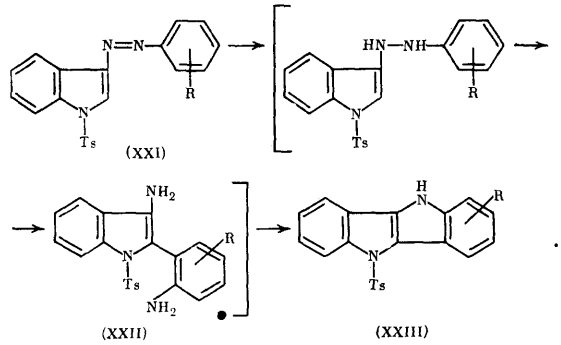
(XVII) (XVIII)

An analogous reaction occurs also for azo-compounds acylated at the pyrrole nitrogen atom[29] and also *N*-acetylin-doxyl arylhydrazones.[30,31] However, in the azo-compounds (XIX), which have a methyl substituent at the indole nitrogen, the dissociation of the N–N bond is accompanied by a semidine rearrangement with formation of 3-acetamido-2-arylamino-1-methylindoles (XX):[31]



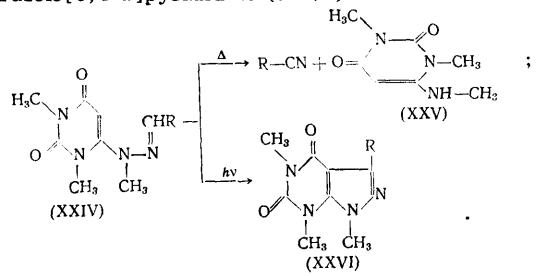
(XIX) (XX)

The reaction involving 3-aryl-1-tosylindoles (XXI) also proceeds with dissociation of the N–N bond accompanied by a rearrangement of the *o*-benzidine type, but the 3-amino-2-(*o*-aminoaryl)indoles (XXII) formed in this process cyclise with elimination of ammonia to give 5-tosylindolo[3,2-*b*]-indoles (XXIII):[32]



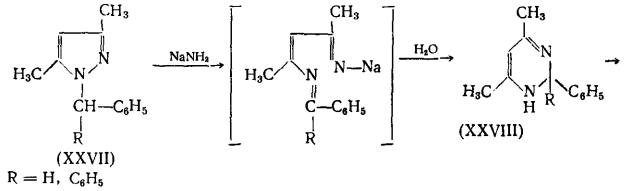
(XXI) (XXII) (XXIII)

Together with the nitrile rearrangement of hydrazones which has been widely investigated in previous studies,[1,33] the thermolysis of 1,3-dimethyl-6-(1-methylhydrazino)uracils (XXIV), which proceeds via a mechanism of the nitrile rearrangement type with dissociation of the N–N bond and the formation of 1,3-dimethyl-6-methylaminouracil (XXV), has been described in the last decade.[34,35] On the other hand, the photolysis of compound (XXIV) takes place without the cleavage of the N–N bond and leads solely to a derivative of pyrazolo[3,4-*d*]pyrimidine (XXVI):[36,37]

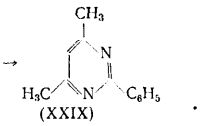


(XXIV) (XXV) (XXVI)

A new rearrangement has been discovered on heating to 155 °C α-benzyl-3,5-dimethylpyrazoles (XVII, R = H or C_6H_5) with sodium amide.[38] In this case the N–N bond of the pyrazole ring is broken with subsequent closure of the 1,2-dihydropyrimidine ring (XXVIII). If the reaction with compound (XXVII, R = H) is carried out at 185 °C, a further aromatisation of compound (XXVIII) is observed and the final product is 4,6-dimethyl-2-phenylpyrimidine (XXIX):

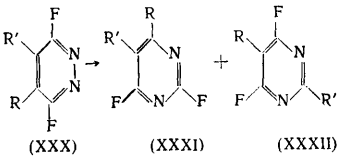


(XXVII) R = H, C_6H_5 (XXVIII)



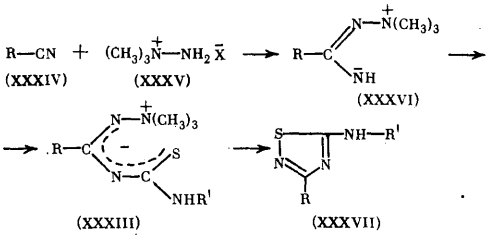
(XXIX)

An interesting thermal rearrangement has been observed for perfluoro-4,5-dialkylpyridazines or 4,5-diperfluoroalkylpyridazines, which are converted at 650 °C into perfluoro-4,5-dialkylpyrimidines (XXXI) and the corresponding diperfluoroalkyl derivatives while in the case of perfluoro-4,5-perfluoroethylpyridazines (XXX) a mixture of perfluoro-4,5-diperfluoroethylpyrimidines (XXXI) and perfluoro-2,5-diperfluoroalkylpyrimidines (XXXII) is obtained:[39,40]



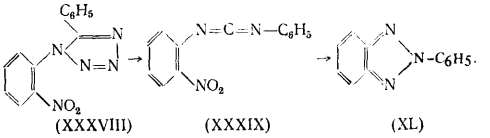
(XXX) (XXXI) (XXXII)

It has been found[41] that the thermolysis of the ylides derived from thiocarbamoylamidrazones (XXXIII) by the reaction of the nitriles (XXXIV) with trimethylhydrazinium chloride of the tosylate (XXXV) and potassium t-butoxide [42] followed by treatment of the ylides of unsubstituted amidrazones (XXXVI) thus produced with aryl or pentyl isocyanates leads to intramolecular nucleophilic attack by the sulphur atom on the N(2) atom with dissociation of the N–N bond, the elimination of triethylamine, and the formation of the corresponding 3-alkyl(aryl)-5-alkyl(aryl)amino-1,2,4-thiadiazoles (XXXVII) in high yields:



(XXXIV) (XXXV) (XXXVI) (XXXIII) (XXXVII)

The thermolysis of 1-(*o*-nitrophenyl)-5-phenyltetrazole (XXXVIII) involves the dissociation of the N–N bonds and the liberation of a nitrogen molecule with subsequent elimination of carbon dioxide from the resulting 1-(*o*-nitrophenyl)-3-phenylcarbodiimide (XXXIX) accompanied by the closure of the triazole ring. 2-Phenylbenzotriazole (XL) is formed in this reaction in yields up to 90%:[43]



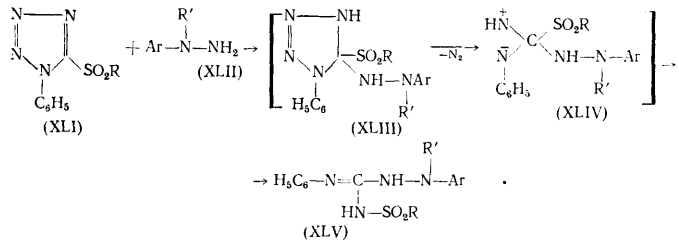
(XXXVIII) (XXXIX) (XL)

The formation of nitrogen and CO in this reaction was confirmed mass-spectrometrically. The corresponding 1-(*p*-nitrophenyl)-5-nitrotetrazole gives rise under these conditions to the thermally stable 1-(*p*-nitrophenyl)-3-phenylcarbodiimide as the main thermolysis product, which confirmed the reaction mechanism postulated by the author.

5-(*o*-Methoxyphenyl)-1-(*o*-nitrophenyl)- and (*oo'*-dimethoxyphenyl)-tetrazoles have been converted analogously in high yields into 2-(*o*-methoxyphenyl)- and 2-(*oo'*-dimethoxyphenyl)-benzotriazoles.[44]

Heating of 5-methanesulphonyl-1-phenyltetrazole (XLI) with arylhydrazines (XLII) above 170 °C leads to vigorous evolution of nitrogen as a result of the thermolysis of the

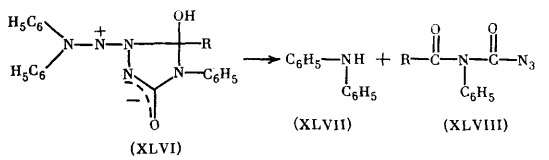
tetrazoline derivatives (XLIII) formed initially. Analogously to the process described previously,[45] the 1,3-dipoles (XLIV) apparently arise under these conditions and in the given instance are stabilised as a result of the migration, via the 2,3-shift mechanism, of the alkanesulphonyl groups from the carbon atom to the vicinal positively charged nitrogen atom with formation of 3-alkanesulphonyl-1-arylamino-2-phenylguanidine (XLV):[46]



(XLI) (XLII) (XLIII) (XLIV) (XLV)

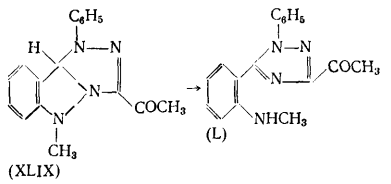
An analogous reaction takes place also when unsubstituted hydrazine is used instead of arylhydrazine.[47]

It has been shown that aminoazimines (XLVI) react at room temperature with bases such as ammonia, aliphatic amines, hydrazines, and aqueous alcoholic solutions of alkali metal hydroxides, being converted into the corresponding amines (XLVII) and azides (XLVIII) with dissociation of the N–N bond:[48]



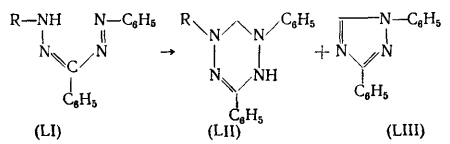
(XLVI) (XLVII) (XLVIII)

Under equally mild conditions, in tetrahydrofuran at room temperature but under the influence of catalytic amounts of concentrated hydrochloric acid, the N–N bond in 3-acetyl-5-methyl-1-phenyl-[1,9*b*]-dihydro-5*H*-1,2,4-triazolo[4,3-*b*]-indazole (XLIX) is broken with formation of 3-acetyl-5-(*o*-methylaminophenyl)-1-phenyl-1,2,4-triazole (L):[49]



(XLIX) (L)

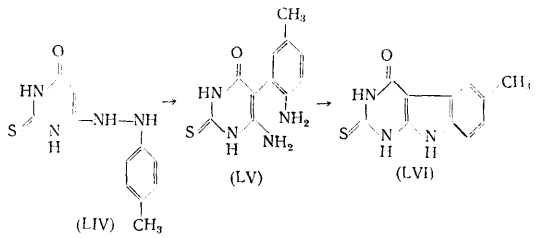
When 1-(2-methyl-5-tetrazolyl)-3,5-diphenylformazan (LI) was treated with formaldehyde, the cleavage of the N–N bond with formation of 1,3-diphenyl-1,2,4-triazole (LIII) was noted together with the closure of the tetrazine ring (LII):[50]



(LI) (LII) (LIII)

Despite its having been studied for a century, the widely known Fischer indole synthesis still continues to be one of the most investigated reactions in the chemistry of heterocyclic compounds. During the last decade alone, a series of new reviews[51–53] and chapters in monographs[6,54] were devoted to this reaction. The development of the concept of the [3,3]sigmatropic shift in the rearrangement stage with cleavage of the N–N bond,[52,56–58] the discovery of the "heterogeneous-catalytic Fischer reaction" [59–63] and its application to the synthesis of unsubstituted indole from acetaldehyde phenylhydrazone,[64] the discovery of the possibility of carrying out the Fischer reaction without acid catalysts ("thermal conversion into indoles",[65,66] conversion into indoles in the presence of bases[67–70] and under the conditions of "extractive base catalysis" [71]), and the discovery of the cationotropic rearrangement of arylhydrazides to 2-aminoindoles[72–77] and of the formation of γ- and δ-halogeno-carboxy-derivatives of indolylalkylamines on conversion of arylhydrazones into indoles[78] must be regarded as the most significant additional advances in the study of the Fischer reaction during this period.

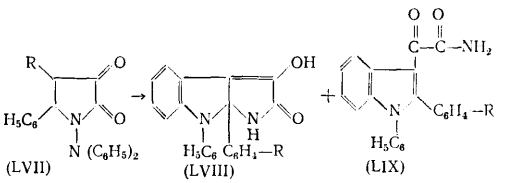
An acid-catalysed [3,3]sigmatropic rearrangement of the type of the Fischer reaction, proceeding with dissociation of the N–N bond, has been discovered for the reaction involving 6-(*p*-tolylhydrazino)-2-thiouracil (LIV). This led to the isolation of 5-(6-amino-3-tolyl)-6-amino-2-thiouracil (LV), which was converted on heating into the corresponding thio-derivative of 9*H*-pyrimido[4,5-*b*]indole-2,4-dione (LVI):[79]



(LIV) (LV) (LVI)

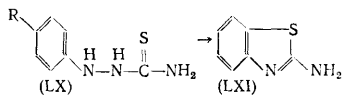
An analogous reaction had been described earlier also for 6-phenylhydrazinouracil.[80,81]

Certain other reactions involving the dissociation of the N–N bond and related to the Fischer indole synthesis have also been investigated. Thus the thermal cyclisation of 1-diphenylamino-2,3-dihydropyrrolidine-2,3-diones (LVII) yielded derivatives of pyrrolo[2,3-*b*]indole (LVIII) and (1,2-diphenyl-3-indolyl)glyoxylic amide (LIX):[82]



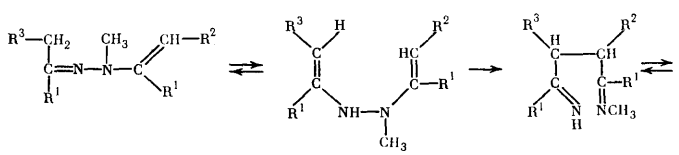
(LVII) (LVIII) (LIX)

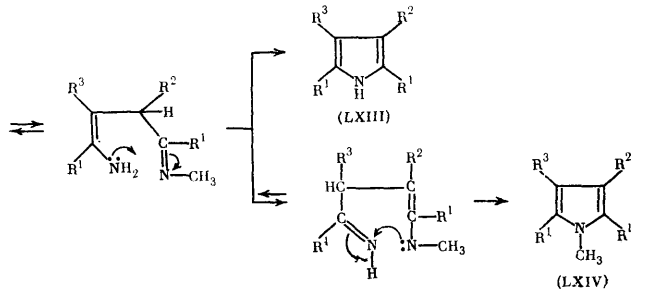
2-Aminobenzothiazoles (LXI) have been isolated in satisfactory yields after the Hugershoff reaction of 1-arylthiosemicarbazides (LX) with alkyl or halogeno-substituents in the benzene ring when these were treated with polyphosphoric acid:[83]



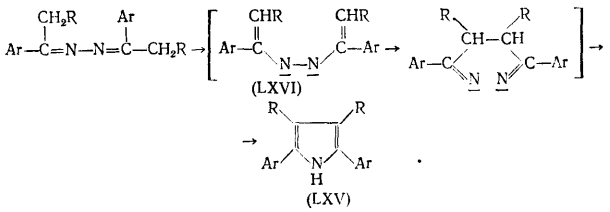
(LX) (LXI)

For the cyclisation of *N*-methylhydrazones of the enolisable ketones (LXII) to substituted pyrroles (LXIII) and (LXIV) under the conditions of the Piloty reaction, using titanium tetrachloride and molecular sieves as catalysts, a mechanism analogous to that of the corresponding reactions of azines has been proposed:[84,85]



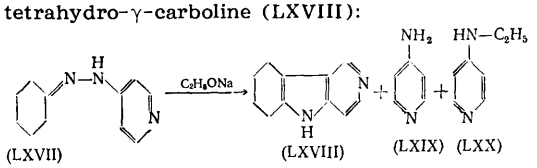


A mechanism involving the [3,3]sigmatropic rearrangement has been postulated as the most likely for a new synthesis of pyrroles (LXV) from the ketazine dianion (LXVI), which takes place in the presence of lithium diisopropylamide in tetrahydrofuran and not in an acid medium, in contrast to the Piloty reaction:[86]



IV. REACTIONS INVOLVING THE DISSOCIATION OF THE N–N BOND WITH SIMULTANEOUS *N*-ALKYLATION

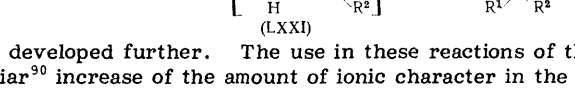
In the course of the study of the Fischer indole synthesis at the beginning of the 1970s, a new type of cleavage of the N–N bond with simultaneous *N*-alkylation was discovered.[87-89] It was found initially that, when cyclohexanone (4-pyridyl)-hydrazone (LVII) is heated with sodium ethoxide, the *N*-unsubstituted 4-aminopyridine (LXV) and 4-(*N*-monoethylamino)pyridine (LXX) are formed simultaneously with the occurrence of the normal Fischer reaction, which leads to the tetrahydro-γ-carboline (LXVIII):



It was shown thereby that the presence of acid catalysts is not an essential condition for the Fischer indole synthesis. Two reactions, which proceed under these conditions simultaneously with the indole synthesis, among which the first is associated with the thermal cleavage of the N–N bond in the hydrazone, apparently via a radical mechanism, and leads to the *N*-unsubstituted aminopyridine (LXIX), while the second has a mechanism apparently involving the intermediate formation of a four-membered cyclic transition state (LXXI), in which the synchronous cleavage of the C–O and N–N bonds is completed by the simultaneous formation of 4-(*N*-monoethylamino)pyridine and the sodio-derivative of cyclohexanone oxime, were observed.

The application of various pyridyl(aryl)hydrazones of aromatic aldehydes in this reaction makes it possible to rule out the possibility of indole synthesis and, by selecting the appropriate temperature, the process can be directed predominantly either towards *N*-unsubstituted or *N*-monoalkyl-substituted pyridyl(aryl)amines.

During the last decade, studies on the N–N bond cleavage reaction with simultaneous *N*-monoalkylation in the reactions of hydrazone and other analogous compounds with alkali metal alkoxides in accordance with the mechanism



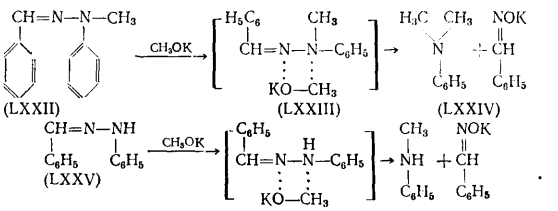
were developed further. The use in these reactions of the familiar[90] increase of the amount of ionic character in the oxygen–alkali metal bond in the sequence Li < Na < K < Rb < Cs made it possible to shift the process significantly, in the case of arylhydrazones. towards the formation of *N*-monoalkylanilines and to achieve 80–90% yields of these compounds in reactions with potassium alkoxides. The analogous reactions with sodium alkoxides take place to an extent not greater than 10% and the main reaction pathway is the thermal decomposition of the arylhydrazones to *N*-unsubstituted anilines.[91,92]

The same influence on the main reaction pathway on passing from sodium to potassium and rubidium alkoxides has also been observed in the synthesis of *N*-monoalkylamino-derivatives of pyrazine, pyridazine, and pyrimidine from the corresponding benzaldehyde diazinylhydrazones and alkali metal alkoxides.[93]

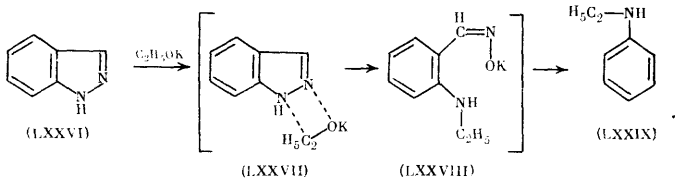
The isolation of 3-aminopyridazine, dibenzylamine, dibenzyl, benzyl alcohol, benzylidene-ethylamine and the products of the reaction of benzaldehyde (3-pyridazinyl)-hydrazone with sodium ethoxide at high temperatures indicates the radical character of the thermal decomposition of the hydrazones. As in other cases, the contribution of this reaction pathway increases with increase of temperature (the yields of the *N*-unsubstituted aminodiazines increase and those of *N*-monoalkylamino-derivatives diminish simultaneously).[93,94]

At the same time special experiments have shown that *N*-unsubstituted heteroaryl(aryl)amines cannot serve as intermediates in the formation of *N*-monoalkylheteroaryl-(aryl)amines, because they do not undergo *N*-alkylation when heated with alkali metal alkoxides at various temperatures.[94]

It is of interest that, when benzaldehyde *N*-methyl-*N*-phenylhydrazone (LXXII) was used as the initial compound in the reaction with potassium methoxide, the formation of a four-membered cyclic transition state (LXXIII) was nevertheless found to be possible despite a definite steric hindrance and the corresponding *NN*-dimethylaniline was obtained in a yield exceeding 20%. The formation of this compound even in trace amounts could not be detected by GLC in the reaction of benzaldehyde phenylhydrazone (LXXV) with potassium methoxide:[94]

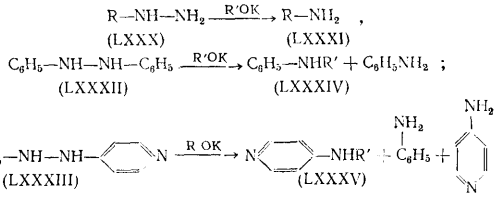


Indazole (LXXVI), which can be regarded as an endocyclic hydrazone, apparently undergoes similar reactions, on heating with potassium ethoxide, via the four-membered (in this instance tricyclic) transition state (LXXVII), in which synchronous dissociation of the C–O and N–N bonds take place. However, the resulting potassium salt of *o*-ethylaminobenzaldehyde oxime (LXXVIII) fragments with elimination of potassium cyanate or its elements and gives rise to a fairly high yield (60%) of *N*-monoethylaniline (LXXIX):[95]

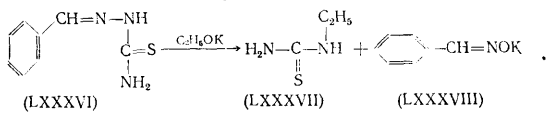


(LXXVI) (LXXVII) (LXXVIII) (LXXIX)

In contrast to *N*-monosubstituted hydrazines, which are cleaved at high temperatures by alkali metal alkoxides to give virtually quantitative yields of the primary amines (LXXXI), only[96] *NN'*-disubstituted hydrazines such as hydrazobenzene (LXXXII) and *N*-phenyl-*N'*-(4-pyridyl)-hydrazine (LXXXIII) give rise under analogous conditions to the corresponding *N*-alkylated amines (LXXXIV) and (LXXXV). The pathway involving the dissociation of the N–N bond with simultaneous alkylation is determined by the electron-accepting character of the residues at the hydrazine nitrogen atoms, which influence the polarity and polarisability of the N–N bond. For example, in the reaction of *N*-phenyl-*N'*-(4-pyridyl)hydrazine (LXXXIII), only 4-(*N*-monoalkylamino)pyridines (LXXXV) are formed and not even traces of *N*-monoalkylanilines can be detected:[94]



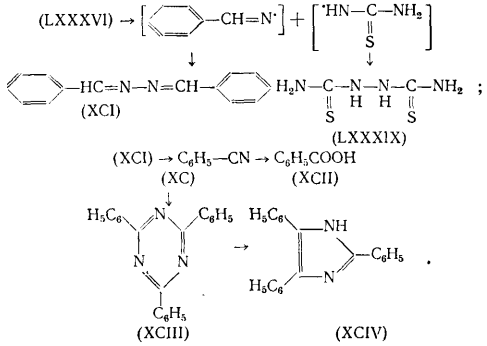
On passing to benzaldehyde thiosemicarbazone (LXXXVI),[97] the reaction with potassium ethoxide also proceeds via the general mechanism and *N*-ethylthiourea (LXXXVII) and the potassium salt of benzaldehyde oxime (LXXXVIII) are formed:



(LXXXVI) (LXXXVII) (LXXXVIII)

As in other analogous reactions, a thermal decomposition of the radical type takes place simultaneously with this process.

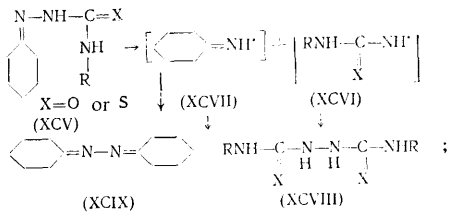
Radical reactions of benzaldehyde thiosemicarbazone (LXXXVI) led to the formation of hydrazodithioformamide (LXXXIX) and benzonitrile (XC) apparently via the benzylideneazine (XCI). On further treatment, the latter partly hydrolyses to benzoic acid (XCII) and, under the reaction conditions, trimerises partly to 2,4,6-triphenyl-1,3,5-triazine (XCIII), which recyclises to the thermally more stable 2,4,5-triphenylimidazole (XCIV):



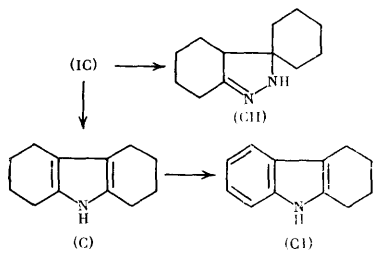
(XCIII) (XCIV)

Benzaldehyde semicarbazone proved to be much more stable and withstood heating with alkali metal alkoxides to 300 °C without any changes.[94,97]

When the semicarbazone (XCV, R = H, X = O), the phenylsemicarbazone (XCV, R = C_6H_5, X = O), and the thiosemicarbazone (XCV, R = H, X = S) of cyclohexanone[98,99] are treated with both alkali metal alkoxides and catalytic amounts of Lewis acids (zinc chloride or tin dichloride), reactions of the Fischer type do not occur and only homolytic dissociation of the N–N bond takes place. It is not accompanied by *N*-alkylation but leads to the *NN'*-diacylated hydrazines (XCVIII) and the cyclohexanone azine (XCIX) as a result of the recombination of the radicals (XCVI) and (XCVII) formed:



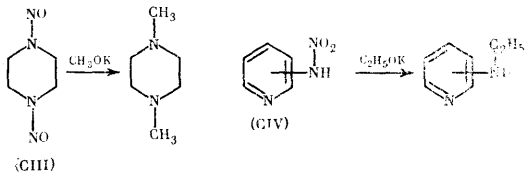
(XCV) (XCVII) (XCVI) (XCIX) (XCVIII)



(C) (CI) (IC) (CII)

[When R = Ph, the radical (XCVI) formed is stabilised as a result of its cleavage to aniline.] According to Kost and Grandberg,[100] cyclohexanone azine (XCIX) is readily converted further into octahydrocarbazole (C) and the product of its partial oxidation by atmospheric oxygen—tetrahydrocarbazole (CI) and also into 5,5-pentamethylene-3,4-tetramethylenepyrazoline (CII).

The increase in the polarity of the N–N bond as a result of conversion into the *N*-nitroso-derivative (CIII) and the *N*-nitroamino-derivative (CIV) facilitates the cleavage of the N–N bond with simultaneous *N*-alkylation on treatment with alkali metal alkoxides:[101,102]



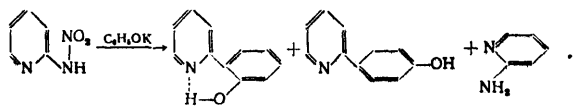
(CIII) (CIV)

The corresponding inorganic nitrites and nitrates are evidently formed as second components of these reactions.

It is of interest that in the case of the isomeric 2-, 3-, and 4-aminopyridines (CIV) the ease of dissociation of the N–N bond with simultaneous *N*-alkylation increases in the sequence 4 < 3 < 2, whereas the opposite sequence of reactivities is characteristic of the analogous isomeric pyridylhydrazones: 2 < 3 < 4.[102] Thus in the preparative synthesis of 3- and 4-monoalkylaminopyridines the best results are produced by the corresponding reactions of benzaldehyde 3- and 4-pyridylhydrazones with alkali metal alkoxides, while the interaction of 2-nitroaminopyridines with alkali metal alkoxides is a more convenient preparative synthetic method for 2-monoalkylaminopyridines.[102]

In contrast to N–N bond dissociation processes with simultaneous alkylation or benzylation, when the corresponding phenoxides are used in the reaction with 2-nitroaminopyridine instead of alkali metal alkoxides benzylates,

denitroamination and arylation in the 2-position in the pyridine ring are observed:[103]



V. ELECTROCHEMICAL AND PHOTOCHEMICAL PROCESSES

The electrochemical and photochemical processes involving the dissociation of the N–N bonds examined in the previous review[1] also developed further during the last decade. It has been shown that, in contrast to the polarographic reduction of the hydrazones (CV) in aqueous alcoholic buffer solutions, which proceeds via the addition of four electrons to the protonated form with formation of amines,[104] in an aprotic medium [dimethylformamide] (DMF) the aryl hydrazones (CV) as well as the thiosemicarbazones or acyl hydrazones of aromatic aldehydes and aliphatic aromatic ketones initially undergo an electrode reaction involving the irreversible addition of one electron to the azomethine group with subsequent cleavage of the N–N bond:[105,106]

$$\underset{\text{(CV)}}{R'-NH-N=CH-R} \rightarrow \dot{N}=CHR + NH_2R' \quad .$$

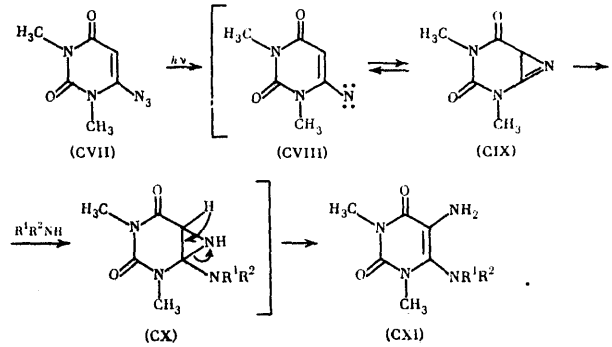
The formation of the corresponding nitriles[107] or their radical-anions[109] as a result of the dissociation of the N–N bond has been demonstrated in relation to the electrochemical reduction of the disubstituted hydrazones of nitrobenzaldehyde and nitrofurfural in DMF. Aminonitrile cleavage has also been noted in the electrochemical reduction of *NN*-disubstituted hydrazones of benzaldehyde and benzoyl chloride (CVI) in an aprotic medium.[109] The following process mechanism has been proposed for the latter case:

$$\underset{\text{Cl}}{C_6H_5-C=N-N(C_6H_5)_2} \underset{\text{(CVI)}}{\xrightarrow[-Cl^-]{+\bar{e}}} C_6H_5\dot{C}=N-N(C_6H_5)_2 \xrightarrow{+\bar{e}} \bar{N}(C_6H_5)_2 + C_6H_5-CN \rightarrow$$

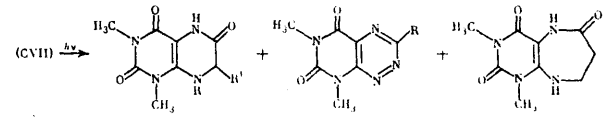
$$\xrightarrow{+\bar{e}} [C_6H_5-CN]^- \quad .$$

In further investigation of the mechanism of the electrochemical reduction of the aminonitrile cleavage of the hydrazone derivatives of nitrobenzaldehyde, it was established that the dissociation of the N–N bond is preceded by deprotonation, at the potentials of the second wave, of the initial depolariser by the dianion formed under these conditions. The mobility of the aldehyde hydrogen atom is then determined by many factors (the basicity, the character of the electronic polarisation of the hydrazone fragment, and the polarity of the N–N bond), discovered in a study of the ^1H NMR spectra and the absorption spectra of the electrochemical oxidation of the substrate at a graphite electrode and justified by quantum-chemical calculations.

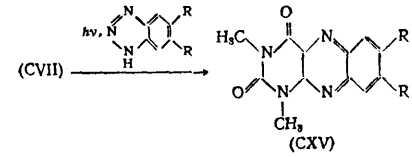
In the course of the development of the previous studies on the photolysis of various azides,[1] the photochemical reactions of 6-azido-1,3-dimethyluracil (CVII) in the presence of various primary and secondary amines have been investigated during the last decade.[111] The above reactions apparently proceed via the intermediate formation of the nitrene (CVIII) with subsequent appearance of the intermediate azirine (CIX). The nucleophilic addition of alkylamines to compound (CIX) and the electrocyclic opening of the aziridine ring (CX) formed complete the synthesis of 6-alkylamino-5-amino-1,3-dimethyluracils (CXI):



Analogous photochemical cleavage reactions of the azides (CVII) with dissociation of the N–N bond, the appearance of the energetically favourable nitrogen molecule, and the formation of a nitrene which undergoes further reactions[112] constitute the basis of the interaction of compound (CVII) with α-aminoacid esters. The final products of these photochemical reactions are lumazines—derivatives of pyrimido(4,5-*b*]-pyrazine (CXII):

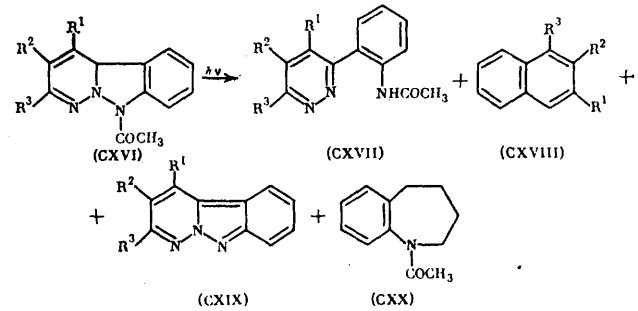


Further development of this method using acylhydrazines as the amine components has led to the synthesis of 7-azalumazines (fervenulins) (CXIII),[111,113] while derivatives of pyrimido[4,6-*b*]diazepines (CXIV) have been obtained from β-aminoacid esters [111] and fervenulins (CXIII) and alloxazines (CXV) have been obtained from tetrazoles and benzotriazoles:[114]



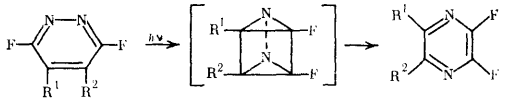
The above reactions are accompanied by the dissociation of the N–N bonds not only in the azide group but also in the cyclic tetrazole (or corresponding benzotriazole) system.

Interesting photochemical reactions with cleavage of the N–N bond have been observed for cyclic 1,3-adducts of *N*-acetyliminopyridazinium ylides with dehydrobenzene (CXVI).[115,116] The photolysis of the corresponding 3-alkoxy-derivatives (CXVI, R^3 = O-alkyl) proceeds with dissociation of the N–N bond and aromatisation accompanied by the formation of 3-(2-acetamidophenyl)pyridazine (CXVII) together with the product of the elimination of molecular nitrogen (acetylnitrene) and subsequent aromatisation [alkoxynaphthalene (CXVII)] as well as the *N*-deacylated aromatic product (CXIX):[116]



The 3-methyl derivative (CXVI), $R^3 = CH_3$, is in the main converted into the *N*-deacetylated aromatic product (CXIX), while compound (CXVI, $R^3 = H$), unsubstituted in the pyridazine ring, is converted into *N*-acetylbenzazepine (CXX) with elimination of molecular nitrogen.[116]

UV irradiation of the tetrafluoropyridazine (CXXI, $R^1 = R^2 = F$) and of its perfluoroalkyl derivatives in the gas phase leads to the corresponding perfluoropyrazines (CXXIII) via the formation of the intramolecular valence isomers of the type of perfluoro-1,2-diazabicyclo[2.2.0]hexa-2,6-diene (CXXII):[117,118]



(CXXI) (CXXII) (CXXIII)

Thus the new studies on the dissociation of the N–N bond have significantly extended the theoretical ideas and preparative possibilities in organic chemistry.

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