Special Paper

CARBALKOXYNITRENES

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1. General

Nitrenes have been the subject of intensive investigation in the past few years by a large number of workers.[1-6]

A nitrene is a monovalent nitrogen species, a member of a class of organic intermediates which contain only six electrons in their valence shell, and are electroneutral. Other members of this class are divalent carbon species, commonly referred to as the carbenes,[7,8] atomatic oxygen,[9] and sulphur.[10] These chemical species have been found to participate in a wide variety of reactions. Other names have been used for such electron deficient nitrogen species[2,4] but the term nitrene is used because of the analogy of its molecular structure with other electron deficient species such as carbenes. Both species are isoelectronic. The name is not intended to reflect anything on its behaviour.

Both, a singlet state with two pairs of electrons and a low energy empty orbital, and triplet state with one electron pair and two electrons with parallel spins are possible, and are known to exist.[4]

It is not our intention to present here exhaustive survey of the whole nitrene chemistry. Instead we will deal with the development and the synthetic applications of carbalkoxynitrenes offering novel reaction paths. A few characteristic reactions will be discussed from the mechanistic point of view.

As early as 1891, nitrenes were proposed in the Lossen rearrangement. Later on they were also postulated as intermediates in the Curtius rearrangement. Since then a large amount of work has been done on the subject, and its scope has been expanded a great deal.

2. Modes of Generation

Nitrenes can be generated in several ways. The most popular way is the thermal and photochemical decomposition of azides. In the case of the reaction of azides with olefins, aziridines are formed. Two possible modes of the formation of aziridines are known. In the first instance the azide adds to the olefin to give triazoline which then goes on to give aziridine with the loss of nitrogen. While in the alternative mode rate determining loss of nitrogen takes place first to give the nitrene which adds to the olefin in the fast step. In the case of the azidoformates or acyl azides, both these modes of addition are observed. As a consequence of the possibility of delocalization of electrons the nitrene exhibits 1,3-cycloaddition reactions to form the oxazolines.
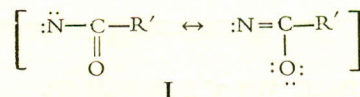
$$\left[\begin{array}{ccc} :\ddot{N}-C-R' & \leftrightarrow & :N=C-R' \\ \quad \| & & \quad | \\ \quad O & & \quad :\ddot{O}: \end{array} \right]$$
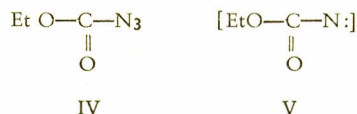I

R′=alkyl, alkoxy, aryl etc.

Again in such cases the aziridines can rearrange to the oxazolines. The latter can also be formed independently of the acylaziridines by a direct 1,3-cycloaddition of the nitrenes.

Carbalkoxynitrenes have also been generated by a non-azide, α-elimination route, from *N-p*-nitrobenzenesulphonoxy urethan, II and III.

$$O_2N-\langle\!\langle \bigcirc \rangle\!\rangle-SO_2NH-CO_2R$$ II: R = Me; III: R = Et
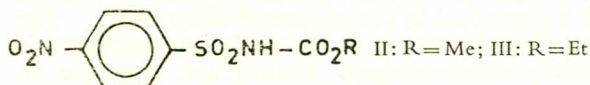
Phenylnitrene similarly can be formed by thermolysis,[12] and photolysis[13] of phenyl azide; the deoxygenation of nitrosobenzene[16] and nitrobenzene;[19] and the photolysis of oxaziranes.[20] The intermediacy of the nitrene is ascertained from the fact that in the presence of dialkylamine, dihydroazepines are obtained from all these substrates, which indicates a common intermediate.

In 1962 the occurrence of ethoxycarbonylnitrene was postulated in the photodecomposition of ethyl azidoformate.[14,15]

$$\begin{array}{cc} \text{Et O}-\text{C}-\text{N}_3 & [\text{EtO}-\text{C}-\text{N:}] \\ \quad\|\ & \qquad\| \\ \quad O & \qquad O \\ \\ \quad IV & \qquad V \end{array}$$

The short-lived intermediate was trapped by its addition to the double bond of cyclohexene, and its insertion in the C—H bond of cyclohexene and cyclohexane.

The nitrenes are rather short-lived, and are invariably generated *in situ*, whence they react fast with the substrate (solvent) to give various products. The nature of the products depends on the substrate used. In the absence of any substrate ethoxycarbonylnitrene dissociates into ethoxy and isocyanate radicals.[17,18]

3. Reactivity

Ethoxycarbonylnitrene whether generated by photolysis,[14,15] thermolysis,[15,21-23] and the α-elimination

route[11] has the same reactivity. This is in striking contrast to the reactivity of carbalkoxycarbenoids. The nitrenes are more selective than the carbenes but both exhibit analogous reactions. The relative reactivity of ethoxycarbonylnitrene for insertion into primary (1°), secondary (2°), and tertiary (3°) C—H bonds of 2-methyl butane were found to be 1:10:34 respectively.[21,24,25] The relative reactivity of methoxycarbonylcarbene for 1° and 2° hydrogens of n-pentane is 1:2.3; for the 1° and 3° hydrogens of 2,3-dimethylbutane is 1:2.9; and in isobutane the reactivity ratio of 1°:3° hydrogens is 1:3.1.[26,27] Ethoxycarbonylnitrene has also been found to be more selective than methylene,[28] in the C—H insertion reactions. This is because of the ready delocalization of electrons in the nitrene, while no such resonance stabilization is possible in the methylene. Thus, it has been found that methylene obtained by the photolysis of diazomethane inserts into the C—H bond at carbon atoms one, two and three of n-pentane in the ratio of 48:35:17 at –75°C, and 49:34:17 at –15°C, which is nearly the statistical distribution. Photolysis in 2,3-dimethylbutane leads to insertion products into the 1° and 3° C—H bonds in the ratio of 17:83, which is again close to statistical figures. Thus it is apparent that in solution methylene shows almost no preference for 2° or 3° C—H bonds. In the gas phase, however, it shows a preference for more highly substituted C—H bonds. Thus Frey and Kistiakowsky[29] found that methylene generated by photolysis of ketene reacts with 2° C—H of n-pentane or n-butane 1.7 times faster than 1° C—H bonds. This ratio could be increased by the addition of some inert gas like argon or carbon dioxide. This is explained in terms of *cooling* (resulting in energy transfer) of initially formed *hot* (vibrationally excited) methylene by collisions with inert gas molecules. Simons and his coworkers[30] have reported that in the presence of triplet scavengers, such as oxygen of nitric oxide, the insertion ratio of methylene into 1° and 2° C—H bonds of n-butane is 1:1.3. In this case methylene is generated by the photolysis of diazomethane or ketene. This lower selectivity of methylene in the presence of oxygen or nitric oxide is explained in terms of the absence of triplet methylene which would abstract H-atoms more selectively to form the most stable radical followed by recombination to give apparent insertion products. In comparison with p-toluensulphonylnitrene VI, it has been found that V is more selective than VI in the C—H insertion reactions. It is postulated that resonance
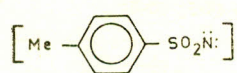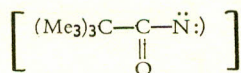
selective than V in the C—H insertion reactions. Their ratios of insertion into 1°:2°:3° C—H bonds are 1:9:160 and 1:7:140 respectively.

From the lifetime of a number of aromatic nitrenes measured in a polystyrene matrix, the rates of H-abstraction have been estimated. It is found that carbonylnitrenes and sulphonylnitrenes are more reactive than the phenylnitrene. This low reactivity of phenylnitrene[32,76] is due to a net negative charge on the nitrogen atom estimated by Hückel molecular orbital method. A linear relationship has been found to exist between the lifetime of the nitrene and the net negative charge on it. In carbonyl- and sulphonylnitrenes the oxygen atom bears the net negative charge due to resonance.

$$\left[\; \overset{..}{:}\overset{|}{N}-\overset{|}{C}=O \;\leftrightarrow\; \overset{+\delta}{:}\overset{|}{N}=\overset{|}{C}-\overset{-\delta}{\overset{..}{\underset{..}{O}}}: \;\right]$$

The relative reactivities of ethoxycarbonylnitrene for insertion into norbornene, adamantane, bicyclo [2.2.2] octane, and tricyclo[3.3.0.0]octane[2,6] are same and comparable to cyclohexane case.[19,46]

Ethoxalyl azide on irradiation by a low pressure mercury arc at –78°C yields ethoxalylnitrene,[78] which exhibits usual nitrene reactions, such as insertion into C—H and O—H bonds and H-abstraction reactions from alkanes and alcohols. It follows the path of reaction in which there is competition between the decomposition of azides to form the nitrene, and its rearrangement to the isocyanate. The reactivity of the nitrene towards the 1°, 2° and 3° C—H bonds of 2-methylbutane is 1:6.6:44.

Kinetic evidence has also been obtained for the nitrene mechanism. It has been found that the azidoformates[23,33-36] decompose thermally in various solvents in clean first order reaction. Only small solvent effects are observed. Thus it was found that the rate of decompositions of IV in tolane, phenylacetylene, diphenyl ether, benzonitrile, and paraffin are nearly independent of the solvent.[37] These results are in good agreement with data on the decomposition of n-octylazidoformate,[34,35] in a number of solvents like diphenyl ether, mineral oil, 1-octadecene, indene, phenol, diglyme, 2-heptanone, diethyl sebacate and pyridine. First order kinetics were observed for the decomposition of both azides and the solvent effects on the rate of decomposition were very small. It thus follows that in these reactions evolution of nitrogen is the rate determining step. The nitrene intermediate so obtained reacts in a fast step with the solvent to give various products.

4. Characteristic Reactions of Carbalkoxynitrenes

The general reaction of the nitrenes are given below for ready reference. A few selected examples will be discussed from the view point of mechanism etc. The details about others may be found elsewhere.

$$\left[\; Me-\!\!\!\bigcirc\!\!\!-SO_2\overset{..}{N}: \;\right]$$

VI

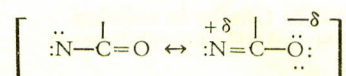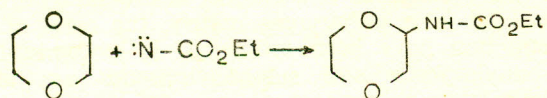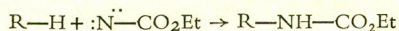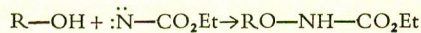$$\left[\; (Me_3)_3C-\overset{\overset{..}{N}:}{\underset{\underset{O}{\|}}{C}} \;\right]$$

VII

stabilization on the carbonyl function in the case of is better than the same effect in VI involving the d-orbitals of sulphur. Pivaloylnitrene[31] VII, and phenylnitrene,[31] however, are found to be more

I. Insertion into C—H Bonds. [11,14,15,21,24,25,31,32,38,39,42,43]

$$R—H + :N—CO_2Et \rightarrow R—NH—CO_2Et$$

(diagram: 1,4-dioxane + :N—CO₂Et → product with NH—CO₂Et)

II. Insertion into O—H Bonds. [11,14,15,21,24,31,32,38,39,44,46]

$$R—OH + :N—CO_2Et \rightarrow RO—NH—CO_2Et$$

III. Insertion into N—H Bonds. [43,45,47]

$$\backslash N—H + :N—CO_2Et \rightarrow \backslash NH—NH—CO_2Et$$
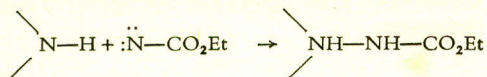
IV. Additions to Olefins in solution in gas phase. [11,14,15,17,18,24,25,38,39,48,50]

$$C=C + :N—CO_2Et \rightarrow \text{(aziridine)} N—CO_2Et$$

$$C=C + :N—CO_2Me \rightarrow \text{(aziridine)} N—CO_2Me$$
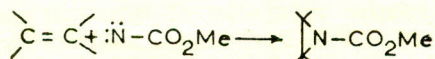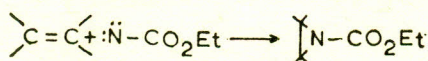
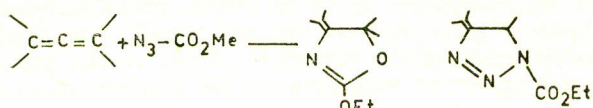Singlet nitrenes add stereospecifically, and triplets add nonstereospecifically.

V. Addition to Alkynes. [33,37,49,51]

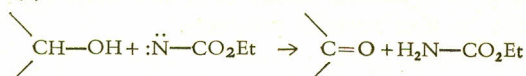$$-C≡C- + :N—CO_2Et \rightarrow \text{(oxazole, OEt)}$$

$$-C≡C- + :N—CO_2Me \rightarrow \text{(oxazole, OMe)} + \text{(=N—CO_2Me)}$$
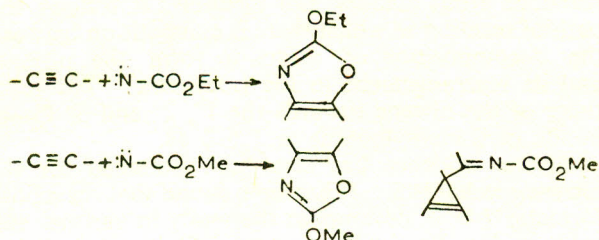
VI. Addition to Allenes. [52]

$$C=C=C + N_3—CO_2Me \rightarrow \text{(oxazoline, OEt)} \quad \text{(triazole, CO_2Et)}$$

VII. Addition to Dienes. [48,53,54]

(butadiene) + :N—CO₂Et → (vinyl aziridine, CO₂Et) (isopropenyl aziridine, CO₂Et)
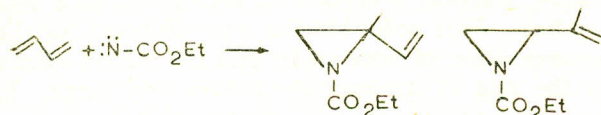
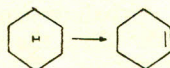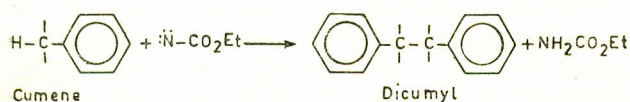**VIII. Dehydrogenation Reaction**
(a) Alcohols. [34,44,47,55]

$$\backslash CH—OH + :N—CO_2Et \rightarrow \backslash C=O + H_2N—CO_2Et$$

(b) Hydrocarbons. [21,23,35]

H—C(Ph) + :N—CO₂Et → (Ph—C—C—Ph) + NH₂CO₂Et

Cumene → Dicumyl

(cyclohexene → benzene diagram)

(c) Hydrazo compounds : [45]

$$EtO_2C—NH—NH—CO_2Et \rightarrow EtO_2C—N=N—CO_2Et$$

IX. Rearrangement. [56,57]

$$:N—CO_2Et \xrightarrow{MeOH} EtO—NH—CO_2Me$$

$$N_3CO_2Me \xrightarrow[\text{or olefin}]{\Delta \text{ in ROH}} MeO—NH—CO_2R + \text{(triazine, OMe)}$$
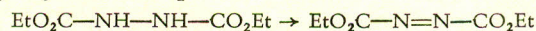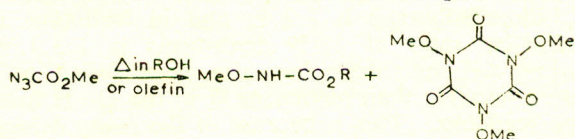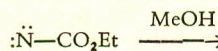
where R=Me, Me₃C

X. Reaction with Aromatic Systems. [11,17,22,25,27,43,58]

(benzene) + :N—CO₂R → (azepine) N—CO₂R
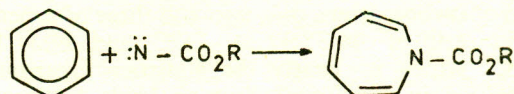
Where R=Et, Ph

Dialkyl-N-carbethoxyazepines formed from the dialkylbenzenes undergo [4+2] Diels–Alder reaction with tetracyanoethylene. [77]

(anthracene) + N—CO₂Et →

(product NH—CO₂Et) + (product NH—CO₂Et)
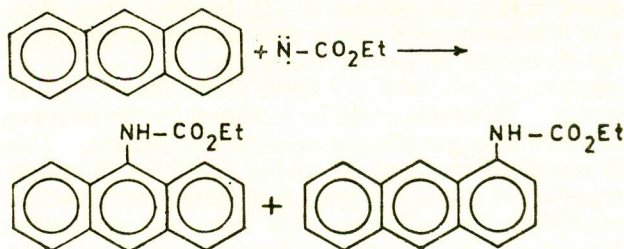
Two different mechanisms involving singlet and triplet nitrenes are operating, resulting in different products.

XI. Reaction with Heterocycles. [59]

(furan) → (pyrrolinone, CO₂Et) (pyrrolinone, CO₂Et)

(pyrrole) → (aminopyrrole, CO₂Et, NH₂) (pyrrole, NH—CO₂Et)

(dimethylthiophene, Me S Me) → (Me N Me, CO₂Et) (Me S Me, NH—CO₂Et)
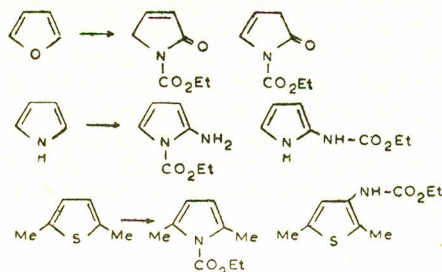
XII. Intramolecular Insertion. [44,55,60,83]

$$[H_3C—CH_2O—C=O, :N:] \rightarrow \text{(oxazolidinone, NH)}$$

$$[(Me_3)C—C=O, :N:] \rightarrow \text{(oxazinone, N H)}$$
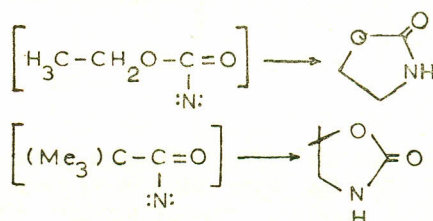
XIII. Reaction with Sulphoxeides. [43,74]

$$Me_2S=O + \ddot{:}N-CO_2R \longrightarrow RO-\overset{\overset{\displaystyle O}{\|}}{C}-N=O + Me_2S$$
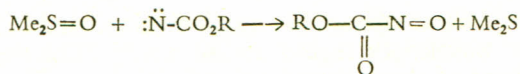
Where R=n-octadecyl

$$Ph-C=O + R_2S=O \longrightarrow Ph-\overset{\overset{\displaystyle O}{\|}}{C}-N=S-R_2$$
$$\overset{\displaystyle |}{:N:} \qquad\qquad\qquad\qquad \overset{\displaystyle \|}{O}$$
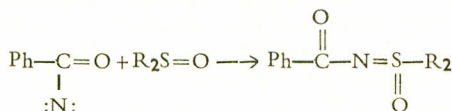
XIV. Reaction with Porphyrins and their Metal Complexes.[62]

The reaction of ethoxycarbonylnitrene with porphyrins leads to products of ring expansion. Their metal complexes give substitutional products.

XV. Addition to Nitriles.[37,49,55,60]

$$R-C\equiv N + \ddot{:}N-CO_2Et \longrightarrow$$

XVI. Reaction with Isonitriles.[61]

$$t\text{-but}-N=C+ \quad :N-CO_2Et \rightarrow t\text{-but}-N=C=N-but\text{-}t$$
$$\qquad\qquad + \qquad -$$

XVII. Reaction with Isocyanates.[40,41]
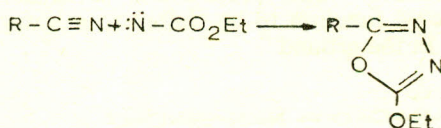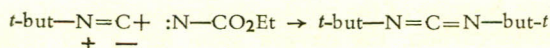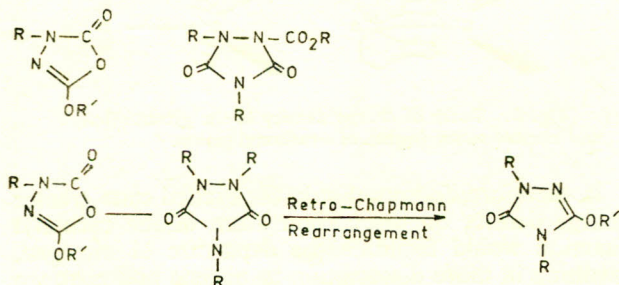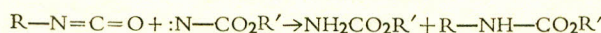
$$R-N=C=O + :N-CO_2R' \rightarrow NH_2CO_2R' + R-NH-CO_2R'$$

Where R=Et, Me; R'=Et, Me

XVIII. Reaction with Tertiary Amines.[40]

$$Et_3N: + :N-CO_2Me \rightarrow NH_2-CO_2ME + Et_2N-CO_2Me$$
$$(-NHCO_2Me)_2 + Et_2N-NH-CO_2Me$$
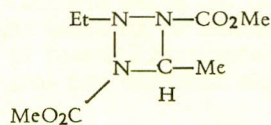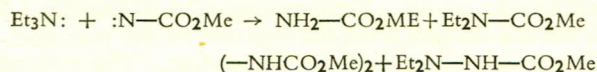
XII

XIX. Addition to Hormones.[74]

Photochemically generated ethoxycarbonylnitrene adds to testosterone acetate, and forms N-(ethoxycarbonyl)-4α,5α-imino-3-oxo- and rostan-17 β-ol-17-acetate, which was characterized from its IR, NMR, electronic and mass spectra.

XX. Reaction with Dialkylacetals of Ketenes.[80]

XXI. Reaction with Ylids.[81]

$$R-S=CH-C=O \xrightarrow[\text{room temp}]{EtO_2CN_3}$$
$$\quad\,\overset{\displaystyle |}{Ph}$$

$$EtO_2C-N=N-NH-\overset{\displaystyle |}{C}=CH-\overset{\displaystyle |}{C}=O$$
$$\qquad\qquad\qquad\qquad C=C \qquad Ph$$
$$\qquad\qquad\qquad\qquad \overset{\displaystyle |}{Ph}$$

After going through the above reaction schemes it may be concluded that carbalkoxynitrenes and carbenes behave similarly, and so do their keto-analogs. Products of formal rearrangement of carbalkoxynitrenes have been characterized,[56,57] and at least in one case[64] a carbalkoxycarbene has been postulated to undergo Wolff rearrangement. In these examples where rearrangement products have been observed, there is no conclusive proof that the 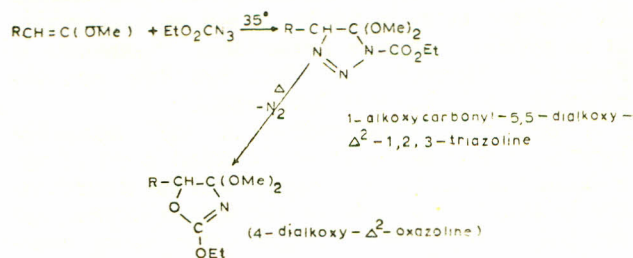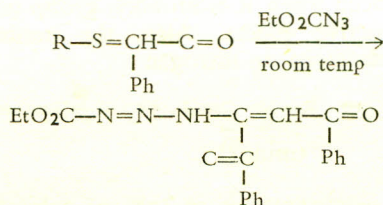carbenes or the nitrenes are the actual intermediate which undergoes rearrangement. Reasonable pathways can be written to account for the rearrangement products from either the carbene or the nitrene precursors. Both in carbalkoxynitrenes, and carbenes, intermolecular reactions such as insertion and addition to multiple bonds are important paths. Formal cycloaddition reactions are common to both carbalkoxy-, and keto-nitrenes and carbenes.

5. Mechanism

The mechanism of the addition of the nitrenes to nitriles and isocyanates is not clear. Three possible pathways, given below, have received attention of different workers, but no conclusive evidence for any one mechanism is available.

I. A 1,3-dipolar cycloaddition of the nitrene to nitriles[60] and isocyanates.[40]

II. Formation of a diazirine,[60] and diaziridinone[40] intermediates, which could later undergo ring expansion to form oxadiazole and oxadiazolin-5-ones respectively. An analogous ring expansion of N-acylaziridines to oxazolines is known.[24,53]

III. Formation of nitrilimine[55] or azomethineimine,[40] and its subsequent ring closure to the products of apparent 1,3-cycloaddition. This type of ring closure has also been reported.[63]

$$R-\overset{\overset{\displaystyle |}{}}{\underset{\underset{\displaystyle Cl}{|}}{C}}=N-NH-CO_2Et \xrightarrow{Et_3N:} R-C=\overset{+}{N}-\overset{-}{N}-CO_2Et \rightarrow$$
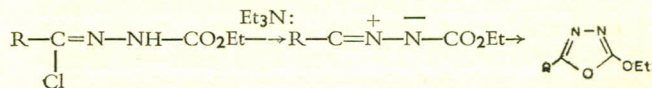
It appears that Huisgen[60] prefers to write a 1,3-dipolar cycloaddition to the nitriles. It is argued that the nitrogen atom in nitriles is not as nucleophilic as in pyridine, where a zwitterionic intermediate is formed.[43] However, this does not rule out the possibility of a diazirine intermediate.

A qualitative consideration of the resonance hybrids of isocyanates from the stand point of the molecular orbital theory indicates that the electron or charge density is greatest on the oxygen (highest net negative charge), the nitrogen atom being intermediate with a net negative charge.[65] The net negative charge on the nitrogen atom should be slightly more pronounced when R is an alkyl group (electron donating inductive effect). Also, the nonbonding long pair of electrons on nitrogen

$$R-N=C-\ddot{O}: \quad \leftrightarrow \quad R-N-C=O \quad \leftrightarrow \quad R-N=C=O$$
$$\overset{+}{} \quad \overset{..}{} \qquad \qquad \overset{-}{} \quad \overset{+}{}$$
(major)   (minor)
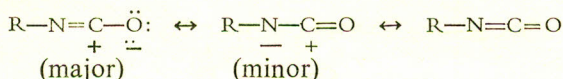
atom in the isocyanates is in the sp^2 orbital. The basicity of a material correlates fairly well with the stability of orbital occupied by nonbonded electrons. The more stable the orbital occupied by nonbonded electrons, the less basic is the material. Thus, aliphatic tertiary amines exhibit pk_{bs} in the region 3–5. Pyridine which has an sp^2 hybridized nitrogen atom has pk_b equal to 9.0, and nitriles which have an sp hybridized nitrogen atom are not usually considered bases. Thus, it seems that isocyanates should coordinate with the nitrene more readily than the nitriles, thus favouring the pathway involving azomethineimine intermediates in the formation of 1,3,4-oxadiazolin-5-ones.[40]

In a photochemical process excitation of a molecule in its ground state can lead to an excited state which is electronically, vibrationally and rotationally excited. It is most probable that ethyl or methyl azidoformate on irradiation are excited to a singlet excited state. The carbalkoxynitrene formed from these would also be in the singlet state. It follows from the principle of spin conservation (energy) that the lowest triplet state of nitrogen is 140 kcal above the ground state. About 15–20% of the photo excited azide decomposes to the nitrene (going on to give the oxadiazolin-5-ones, and other products of H-abstraction etc.), while the rest is converted to vibrationally excited azide by internal conversion. In the thermal reaction this restriction does not apply, and the vibrationally excited azide reacts with substrate, while little (less than 15%) is dissociated to the nitrene and nitrogen.

It has been found[40] that the irradiation by the longer wavelength (300 nm, lower energy) light leads to the $n-\pi^*$ transition of the azide chromophore. These $n-\pi^*$ transitions are localized on the chromophore responsible for excitation.[66,67] Ethylazide has an absorption band at 287 nm (ε 20).[67] For the azide chromophore case this $n-\pi^*$ transition would be symmetry forbidden resulting in the low ε-value.[67] Immediately after the transition internal conversion takes place, resulting in the vibrationally excited azide which could react with the isocyanate. In the case of lower wavelength (253.7 nm) light the $n-\pi^*$ transition of the carbonyl chromophore takes place. The

carbonyl chromophore has an absorption band in the longer wavelength region at 280 nm.[66] The $n-\pi^*$ transition of the carbonyl group involves an electron transfer from the oxygen towards the carbon atom. Any group which militates against this transfer will shift the $n-\pi^*$ transition bands to higher energy, i.e. lower wavelength.[67] Methyl azidoformate absorbs in the UV at 300 and 254 nm with an extinction coefficient of 2.02 and 85.00 respectively.[40] The corresponding values for the ethyl azidoformate are 2.7 and 88.1.[38]

In the alkyl azidoformates, we note that it has an electron donating alkoxy group attached to the carbonyl, also one of the resonance forms of this azide has a net negative charge on the nitrogen atom adjacent to the carbonyl function, and this negative charge can be delocalized over the carbonyl function, which probably would cause the $n-\pi^*$ transition of the carbonyl function to be shifted to a lower wavelength. In the ground

$$N=N-N-C=O \quad \leftrightarrow \quad N=N-N=C-\ddot{O}:$$
$$\overset{+}{}\overset{-}{} \qquad \qquad \qquad \overset{..}{}$$
OR   OR
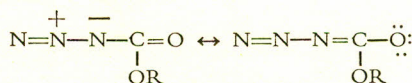
state, because of the greater electronegativity of oxygen versus carbon, the oxygen atom has a net negative charge. In contrast, in the excited state the charge density is greater on the carbon atom of the carbonyl function than oxygen atom (Fig. 1).[66,67]

Fig. 1.   Form of charge density in the ground (left) and excited states (right) of a carbonyl group.

It, therefore, follows that in the excited state greater charge density on the carbon atom of the carbonyl function would facilitate the departure of nitrogen, resulting in more dissociation to nitrene and nitrogen than in the case of photolysis by 300 nm light in which case azide chromophore is excited instead of the carbonyl group.

It has been shown[40,41] that the oxadiazolin-5-ones are formed by the reaction of the nitrene with the isocyanate, while 2-carbalkoxy-1,2,4-triazolidin-3,5 diones are formed from the reaction of the vibrationally excited azide with the isocyanate. The nitrene was ruled out as the precursor for these compounds. It is explained by an initial attack of the azide group on the isocyanate followed by addition of one more isocyanate molecule and loss of nitrogen.[40]
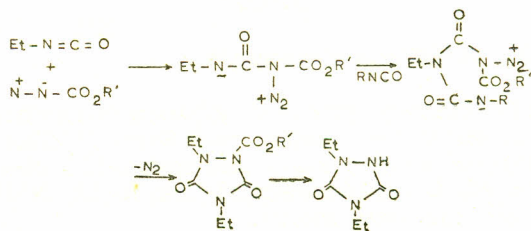
This path offers a very attractive method for the synthesis of such triazoles, which otherwise are obtained by very cumbersome paths. The 2-carbalkoxy-1,2,4-triazolidin-3,5-diones can be hydrolysed to 1,4-diethyl urazoles, which in turn can be alkylated by diazoalkanes to various substituted trialkyl urazoles.

In the study of the reactions of tertiary amines with the nitrenes, Hafner[43] found that with dimethyl aniline insertion of the nitrene into the C—H bond of methyl group takes place.

$$Ph—N(CH_3)_2 + :N—CO_2Et \rightarrow Ph—N—CH_2NH—CO_2Me$$
$$\underset{Me}{|}$$
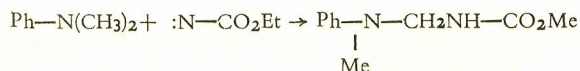
Thermal decomposition[43] of ethyl azidoformate in pyridine give the N,N-betaine in 67% yield.
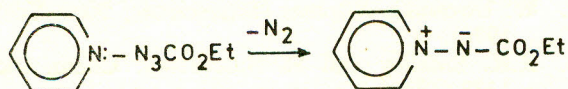
Ashley and his coworkers[68] found that on thermal decomposition of p-acetamidobenzenesulphonyl azide in excess pyridine, a crystalline solid is formed, which is quite stable.
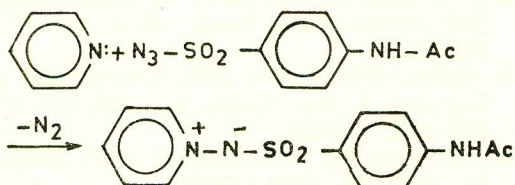
Carbenes have also been found to react with tertiary amines. Thus Saunders and Murray[69] found that dichlorocarbene reacts with triethylamine to yield N,N-diethylformamide.

$$Et_3N: + :CCl_2 \rightarrow Et_3\overset{+}{N}—\overset{-}{C}—Cl_2 \xrightarrow{C_2H_4} Et_2N—CHCl_2$$
$$\xrightarrow{H_2O} Et_2N—CH=O$$
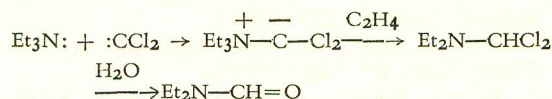
Ethoxycarbonylcarbene from the decomposition of ethyl diazoacetate reacts with triethylamine to form N,N-diethylglycine, in addition to products of insertion.

$$Et_3N: + :CH—CO_2Et \rightarrow Et_3\overset{+}{N}—\overset{-}{CH}—CO_2Et \rightarrow$$
$$Et_2N—CH_2—CO_2Et$$
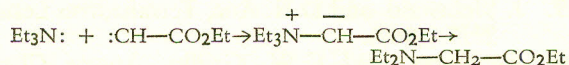
In these reactions of carbenes with tertiary amines a ylid or zwitterionic intermediate is usually postulated which undergoes further reaction to give the final product. In the case of nitrenes a betaine or azomethineimines are the intermediates which have been isolated in certain cases.

Nitrogen ylids differ from phosphorus or sulphur ylids in that nitrogen is a first row element with filled $2s$ and $2p$ orbitals. The next available empty orbital is the $3s$ which is at considerable higher energy level and, therefore, is not available for overlapping. Consequently the nitrogen bearing the positive charge can stabilize the adjacent anion only by an electrostatic interaction between the opposite charges.

In the study of ethoxycarbonylnitrene with amines[45] its reaction with triethylamine went unnoticed for quite sometime and, therefore, it was generally assumed that triethylamine is 'inert' to the nitrenes. However, this contention seemed quite puzzling since the pk_b of triethylamine is 3.1 in comparison to about 9.0 for pyridine, and since the nitrene is an electron deficient species, therefore, it was logical to expect that Et_3N should coordinate with the nitrene. This was found to be true when during the investigation[40] of the reaction with isocyanates, methoxycarbonylnitrene was generated by α'-elimination from II, using triethylamine as the base. In this reaction certain products were obtained which could not be explained just from the reaction of the isocyanate and the nitrene. On further investigation in a detailed study, it was revealed that triethylamine does react with methoxycarbonylnitrene to give five products (cf. reaction no. XVIII). It was found[40] that a betaine intermediate is formed in this reaction which may be short-lived. This betain goes on to form various products according to a similar path as proposed by Saunders and Murray[69] for the dichlorocarbene reaction. An extension of this pathway accounts

$$Et_3N: + :\overset{..}{N}—CO_2Me \rightarrow Et_3\overset{+}{N}—\overset{-}{N}—CO_2Me$$
$$\xrightarrow{-C_2H_4} Et_2N—NH—CO_2Me$$
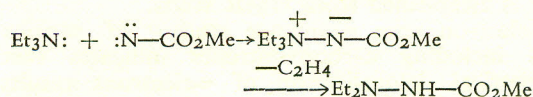
for the triazetidine derivative XII for which the following structure is favoured over the alternative one, on the basis of mass spectrum.
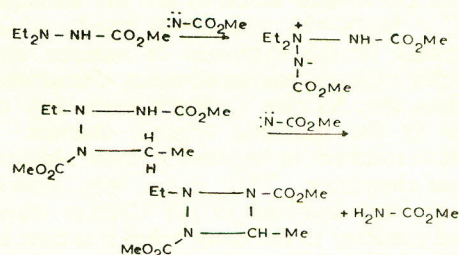

This is the first example of the triazetidine structure for the existence of which a reasonable evidence has been given. In the past reports of the formation of triazetidine have been found to be lacking in evidence.[70]

Wilde and his coworkers[71] found that methyl azidoformate on photolysis in a neon–argon matrix undergoes two reactions. The initial product which could not be identified (has an IR band at 2211 cm^{-1}) undergoes photolysis to final products, which include methoxyisocyanate, formaldehyde and isocyanic acid (their identification is based on their IR spectra). They assigned certain bands in the vibrational spectrum to formaldehyde–isocyanic acid molecule pair. The results suggest two possible modes of decomposition of methyl azidoformate, which could be conformationally dependent. One of these possibilities is the competition between the dissociation of the excited azide to give the nitrene and its internal conversion to a vibrationally excited molecule. The latter could undergo rearrangement. A similar scheme has earlier been proposed in the reactions of alkyl azidoformates

with isocyanates. The rearrangement product, methoxy isocyanate gives on photolysis formaldehyde and isocyanic acid. No nitrene is involved in the rearrangement. It is reasonable to assume that the azide being unable to decompose via nitrene because of the cage effect in the matrix, it is converted to vibrationally excited azide.

6. Alkoxynitrenes

Recently alkoxynitrenes[82] have been postulated in the lead tetracetate oxidation of methoxyamine, in the presence of tetramethylethylene to give 1-methoxy-2,2,3,3-tetramethylaziridine. Singlet alkoxynitrene, believed to be in the ground state, is involved. The nitrene is stabilized by the delocalization of electrons.

$$\left[Me-O-\ddot{N}: \quad \leftrightarrow \quad Me-O\overset{+}{=}\overset{-}{\ddot{N}} \right]$$
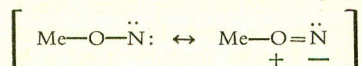
This evidently is the first example for the existence of alkoxynitrene. The alkoxyaziridines so formed exhibit considerable energy barrier to nitrogen inversion, and exist as stable pyramids at room temperature, as is established from NMR study.

The electron spin resonance study[72] of various nitrenes including carbonylnitrenes indicates that unsymmetrical delocalization of π-electrons results in spin splitting of various signals in case of triplet nitrenes.

In conclusion it is easy to visualize the tremendous potential the nitrenes have as synthetic intermediates. They offer convenient methods for the formation of C—N, C = N, N—N, and O—N bonds, which are demonstrated in the synthesis of various complex heterocycles such as oxadiazolinones, triazolidinones, triazetidines etc. As nice synthetic tools they offer a challenge to the synthetic organic chemist. Their studies have resulted in improving some old concepts of organic chemistry. Thus it has been shown that nitrenes are not involved in the Curtius rearrangement, and contrary to the early belief it is now known that some of the 'rigid' azides do undergo rearrangement.[56,57,71] Diethylcarbamoyl azide is one of these 'rigid' azides which undergoes rearrangement on photolysis[79] to form dialkylaminoisocyanates, which have been trapped as 1:1 adducts with alkyliso-cyanates giving 1,2,4-triazolidin-3,5-dion-1,2-ylids. This appears to be a nicesynthetic approach to triazolidinones.

7. Uses

Apart from usual synthetic reactions carbalkoxy-nitrenes have also found uses in commercial processes. They are used in the vulcanization[75] of both saturated and unsaturated elastomers. First order decompositions of alkylene bis-azidoformates yield the nitrenes which react with the polymer chain, to give heat resistant vulcanizates having excellent physical properties.

8. Precautions

Finally a word of warning about the preparation of azidoformates from the reaction of carbonyl chloride with alcohols and their subsequent reaction with sodium azide. Extreme care should be exercised to remove all carbonyl chloride before reacting with sodium azide. Otherwise carbonyl azide which is extremely explosive may be formed to give undesirable results. Also the azidoformates themselves should be handled with care as on dropping they may cause violent explosions.

References

1. L. Horner and A. Christman, Angew Chem. Intern. Ed., **2**, 599 (1963).
2. R.A. Abramovitch and B.A. Davis, Chem. Rev., **64**, 149 (1964).
3. O.M. Nefedov and M.N. Manakov, Angew. Chem. Intern. Ed., **5**, 1021 (1966).
4. W. Lwowski, ibid., **6**, 897 (1967).
5. W. Lwowski, Nitrenes (Interscience, New York, 1970).
6. R.K. Smalley and H. Suschitzky, Chem. Ind., 1338 (1970).
7. W. Kirmse, Carbene Chemistry (Academic Press, New York, 1964).
8. J.S. Hine, Divalent Carbon (Ronald Press, New York, 1964).
9. R.J. Cvetanovic, Advances in Photochemistry, (Interscience, New York, 1963), vol. I, pp. 115–182.
10. K. Sidhu, E.M. Lown, O.P. Strausz and H.E. Gunning, J. Am. Chem. Soc., **88**, 254 (1966) and refs. therein.
11. W. Lwowski, T.J. Maricich and T.W. Mattingly Jr., ibid., **85**, 1200 (1963).
12. R. Huisgen, D. Vossius and M. Appl., Chem. Ber., **91**, 1, 12 (1958).
13. W.v.E. Doering and R.A. Odum, Tetrahedron, **22**, 81(1966).
14. W. Lwowski and T.W. Mattingly Jr., Tetrahedron Letters, 277 (1962).
15. W. Lwowski and T.W. Mattingly Jr., J. Am. Chem. Soc., **87**, 1947 (1965).
16. J.H. Boyer, Nitrenes (Interscience, New York, 1970), p. 163,
17. S. Berry, D.W. Cornell and W. Lwowski, J. Am. Chem. Soc., **85**, 1199 (1963).
18. D.W. Cornell, R.S. Berry and W. Lwowski, ibid., **87**, 3626 (1965).
19. J. Meinwald and D.H. Aue, Tetrahedron Letters, 2317 (1967).
20. E. Meyer and G.W. Griffin, Angew Chem., **79**, 648 (1967).
    J.S. Splitter and M. Calvin, Tetrahedron Letters, 1445 (1968).
21. M.F. Sloan, T.J. Prosser, N.R. Newburg and D.S. Breslow, Tetrahedron Letters, 2945 (1964).
22. R.J. Cotter and W.E. Beach, J. Org. Chem., **29**, 751 (1964).
23. D.S. Breslow, T.J. Prosser, A.F. Marcantonio, and C.A. Genge, J. Am. Chem. Soc., **89**, 2384 (1967).
24. W. Lwowski and T.J. Maricich, ibid., **86**, 3164 (1964).
25. W. Lwowski and T.J. Maricich, ibid., **87**, 3430 (1965).

26. W.v.E. Doering, and L.H. Knox, *ibid.*, **78**, 4947 (1956); *ibid.*, **83**, 1989 (1961).
27. A.L.J. Beckwith and J.W. Redmond, Chem. Commun., 165 (1967); J. Am. Chem. Soc., **90**, 1351 (1968); Australian J. Chem., **19**, 1859 (1966).
28. W.v.E. Doering, R.G. Buttery, R.G. Laughlin and N. Chaudhuri, J. Am. Chem. Soc., **78**, 3224 (1956).
29. H.M. Frey and G.B. Kistiakowsky, *ibid.*, **79**, 6373 (1957).
30. J.W. Simons, C.J. Mazac and G.W. Taylor, J. Phys. Chem., **72**, 749 (1968).
31. G.T. Tissue, S. Linke and W. Lwowski, J. Am. Chem. Soc., **89**, 6303 (1967).
32. J.H. Hall, J.W. Hill and H.C. Tsai, Tetrahedron Letters, 2211 (1965).
33. R. Huisgen and H. Blaschke, Chem. Ber., **98**, 2985 (1965).
34. T.J. Prosser, A.F. Marcantonio and D.S. Breslow, Tetrahedron Letters, 2479 (1964).
35. T.J. Prosser, A.F. Marcantonio, C.A. Genge, and D.S. Breslow, *ibid.*, 2483 (1964).
36. D.S. Breslow and E.I. Edwards, *ibid.*, 2123 (1967).
37. R. Huisgen and H. Blaschke, *ibid.*, 1409 (1964).
38. T.W. Mattingly Jr., doctoral dissertation, Yale University, August 1964.
39. T.J. Maricich, doctoral dissertation, Yale University, August 1965.
40. S.M.A. Hai, doctoral dissertation, New Mexico State University, March 1969.
41. W. Lwowski and S.M.A. Hai, "Symposium of Small Ring Heterocycles", Washington, A.C.S. meeting, September 12-17 (1971), Abstr. No. 63.
42. H. Nozaki, S. Fujita, H. Takaya and R. Noyari, Tetrahedron, **23**, 45 (1967).
43. K. Hafner, D. Zinser and K.L. Moritz, Tetrahedron Letters, 1733 (1964).
44. R. Kreher and G.N. Bockhorn, Angew. Chem., **76**, 681 (1964).
45. L.H. Selman, doctoral dissertation, Yale University, August 1966.
46. D.S. Breslow, E.I. Edwards, R. Leone and P. von Schleyer, J. Am. Chem. Soc., **90**, 7097 (1968).
47. L. Horner, G. Bauer and J. Dorges, Chem. Ber., **8**, 2631 (1965).
48. K. Hafner, W. Kaiser and R. Puttner, Tetrahedron Letters, 3953 (1964).
59. R. Huisgen and J.P. Anselme, Chem. Ber., **98**, 2998 (1965).
50. A.C. Oehlschlager, R.S. McDaniel, A. Thakore, P. Tillman and L.H. Zalkow, Canad. J. Chem., **47**, 4367 (1969).
51. J. Meinwald and D.H. Aue, J. Am. Chem. Soc., **88**, 2849 (1966).
52. R.F. Bleiholder and H. Shechter, *ibid.*, **90**, 2131 (1968).
53. A. Mishra, S.N. Rice and W. Lwowski, J. Org. Chem., **33**, 481 (1968).
54. S. Masamune and N.T. Castellucci, Angew, Chem., **76**, 569 (1964).
55. R. Puttner and K. Hafner, Tetrahedron Letters, 3119, (1964).
56. W. Lwowski, R. deMauriac, T.W. Mattingly Jr. and E. Scheifele, *ibid.*, 3285 (1964).
57. R. Puttner, W. Kaiser and K. Hafner, *ibid.*, 4315 (1968).
58. K. Hafner and C. Konig, Angew. Chem. Intern. Ed. Engl., **2**, 96 (1963).
59. K. Hafner, and W. Kaiser, Tetrahedron Letters, 2185 (1964).
60. R. Huisgen and H. Blaschke, Ann. Chem., **686**, 145 (1965).
61. W. Lwowski, M. Grassman and T. Shingaki (unpublished results).
62. R. Grigg, Chem. Commun., 1238 (1967).
63. T. Bacchetti, Gazz. Chim. Ital., **91**, 866 (1961); Chem. Abstr., **56**, 8708 (1962).
64. O.P. Strausz, T. DoMinh and H.E. Gunning, J. Am. Chem. Soc., **90**, 1660 (1968).
65. R.G.M. Arnold, J.A. Nelson and J.J. Verbanc, Chem. Rev., **57**, 47 (1957).
66. N.J. Turro, *Molecular Photochemistry* (Benjamin, New York, 1967), p. 13.
67. J.N. Murrel, *The Theory of Electronic Spectra of Organic Molecules* (J. Wiley, New York, 1963), p. 82.
68. J.N. Ashley, G.L. Buchanan and A.P.T. Easson, J. Chem. Soc., 60 (1947).
69. M. Saunders and R.W. Murray, Tetrahedron, **11**, 1 (1960).
70. R.C. Kerber and A. Porter, J. Org. Chem., **33**, 3663 (1968).
71. R.E. Wilde, T.K.K. Srinivasan and W. Lwowski, J. Am. Chem. Soc., **93**, 860 (1971).
72. E. Wasserman, Progr. Phys. Org. Chem., **8**, 319 (1971).
73. H. Yajima, H. Kawatani and Y. Kiso, Chem. Pharm. Bull., **18**, 850 (1970).
74. R.P. Gandhi and M. Singh, Indian J. Chem., **8**, 485 (1970).
75. D.S. Breslow, W.D. Willis and L.O. Amberg, Rubber Chem. Technol., **43**, 605 (1970).
76. A. Reiser and L. Leyshon, J. Am. Chem. Soc., **92**, 7487 (1970).
77. J.M. Photis, J. Heterocycl. Chem., **7**, 1249 (1970); *ibid.*, **8**, 167 (1971).
78. T. Shingaki, M. Inagaki, M. Takebayashi, R. Lebkuecher and W. Lwowski, Bull Chem Soc. (Japan), **43**, 1912 (1970).
79. W. Lwowski, R.A. deMauriac, R.A. Murray and L. Lunow, Tetrahedron Letters, 425 (1971).
80. R. Scarpati and M.L. Graziano, *ibid.*, 2085 (1971).
81. E. Van Loock, G. Labbe and G. Smets, *ibid.*, 1963 (1970).
82. S.J. Brois, J. Am. Chem. Soc., **92**, 1079 (1970).
83. I. Brown and O.E. Edwards, Canad. J. Chem., **45**, 2599 (1967).