The Thermolysis and Photolysis of Diazirines

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1 Introduction

The chemistry of diazirines has a relatively short history dating from the discovery of these compounds in 1960 by Paulsen,[1] and Schmitz and Ohme.[2] Since then the three-membered ring isomers of diazoalkanes have received increasing interest and the progress in this field has been reviewed.[3-11] The structure of the three-membered ring compounds was first elucidated in 1962. Both the dipole moment and the quadrupole coupling constants were reported and shown to be consistent with a cyclic structure.[12] It was also demonstrated that the two nitrogen atoms are equivalent.[13]

The mode of preparation of diazirines depends on their functional groups. Alkyl and aryl diazirines are easily synthesized by using the appropriate aldehyde or ketone [equation (1)].[14] Graham reported that the oxidation of amidines by hypochlorites (or hypobromites) gives chloro- (or bromo) -diazirines.[15]

Spectral characteristics are most commonly used in the identification of these compounds. For example, in the infrared absorption spectrum the N=N stretching frequency is 1560—1585 cm^{-1} whereas the ultra-violet absorption is consistently in the 350—400 nm range.

These cyclic compounds are remarkably stable towards organic and inorganic reagents,[16] in sharp contrast to the behaviour of their linear isomers. They are

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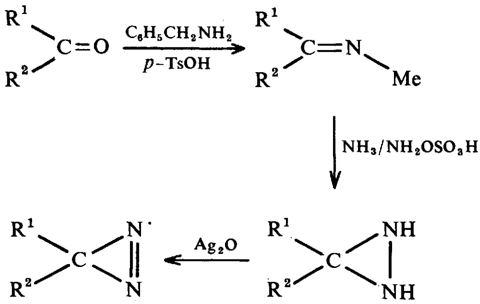
[1] S. R. Paulsen, *Agnew. Chem.*, 1960, **72**, 781.
[2] E. Schmitz and R. Ohme, *Angew. Chem.*, 1961, **73**, 115.
[3] E. Schmitz, *Adv. Heterocycl. Chem.*, 1979, **24**, 63.
[4] E. Schmitz, 'Dreiringe mit Zwei Heteroatomen', Springer-Verlag, New York, 1967.
[5] P. S. Engel, *Chem. Rev.*, 1980, **80**, 99.
[6] H. M. Frey, *Adv. Photochem.*, 1966, **4**, 225.
[7] S. Braslavsky and J. Heicklen, *Chem. Rev.*, 1977, **77**, 473.
[8] H. Meier and K.-P. Zeller, *Angew. Chem., Int. Ed. Engl.*, 1977, **16**, 835.
[9] J. B. Moffat, in 'The Chemistry of Diazonium and Diazo Groups' Pt. 1, ed. S. Patai, Wiley-Interscience, New York, 1978.
[10] W. Kirmse, 'Carbene Chemistry', Academic Press, New York, 1971.
[11] M. Jones Jr. and R. A. Moss, 'Carbene' Vol. 1, Wiley-Interscience, New York, 1973.
[12] L. Pierre and V. Dobyns, *J. Am. Chem. Soc.*, 1962, **84**, 2651.
[13] E. Schmitz, R. Ohme, and R. D. Schmidt, *Chem. Ber.*, 1962, **95**, 2714.
[14] E. Schmitz and R. Ohme, *Tetrahedron Lett.*, 1961, 612.
[15] W. H. Graham, *J. Am. Chem. Soc.*, 1965, **87**, 4396.
[16] It is advisable to take extreme precautions when working with neat diazirine in all phases. It is recommended that all diazirines should be handled in diluted state only. *cf.* M. T. H. Liu, *Chem. Eng. News*, Sept. 9, 1974, p. 3; M. J. Leleu, *Cahiers De Notes Documentaires* No. 93, 1978, p. 569.



(1)

resistant to alkalis or strong acids and are only decomposed by 80% sulphuric acid.

Because of their stability, diazirines have been investigated as a source of carbene following thermolysis or photolysis. Most photochemical studies have been carried out in the gas phase,[6,7] but many thermal decompositions have been studied both in the gas phase[17-21] and in solution.[22-26]

Reports have appeared on the photolysis of diazirines trapped in solid matrices,[27,28] in which the nature of the intermediate formed during the decomposition was studied. The first examples of substituted diazirinyl radicals[29] have also been obtained by photolysis of the parent bromides in the presence of hexa-n-butylditin.

In this review the kinetic aspects of thermolysis and photolysis of diazirines are discussed, as these two topics complement each other in the understanding of the underlying mechanisms.

2 Thermolysis of Diazirines

Frey and Stevens[21] have investigated the gas-phase thermal decomposition of 3,3-dimethyldiazirines over the range 124—174 °C. They found that the reaction is homogeneous and first-order and gives only propene and nitrogen. Propene does not inhibit the reaction; thereby providing evidence for the absence of any radical-chain contribution and strongly suggesting that the decomposition is simple and unimolecular. The decomposition is pressure-dependent below

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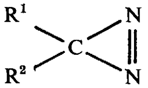
[17] H. M. Frey and A. W. Scaplehorn, *J. Chem. Soc., A*, 1966, 968.
[18] E. W. Neuvar and R. A. Mitsch, *J. Phys. Chem.*, 1967, **71**, 1229.
[19] M. R. Bridge, H. M. Frey, and M. T. H. Liu, *J. Chem. Soc., A*, 1969, 91.
[20] H. M. Frey and M. T. H. Liu, *J. Chem. Soc., A*, 1970, 1916.
[21] H. M. Frey and I. D. R. Stevens, *J. Chem. Soc.*, 1962, 3865.
[22] M. T. H. Liu and K. Toriyama, *Int. J. Chem. Kinet.*, 1972, **4**, 229.
[23] M. T. H. Liu and K. Toriyama, *J. Phys. Chem.*, 1972, **76**, 797.
[24] B. M. Jennings and M. T. H. Liu, *J. Am. Chem. Soc.*, 1976, **98**, 6416.
[25] M. T. H. Liu and B. M. Jennings, *Can. J. Chem.*, 1977, **55**, 3596.
[26] N. P. Smith and I. D. R. Stevens, *J. Chem. Soc., Perkin Trans. 2*, 1979, 213.
[27] C. B. Moore and G. C. Pimentel, *J. Chem. Phys.*, 1964, **41**, 3504.
[28] O. L. Chapman, C. C. Chang, J. Kolc, M. E. Jung, J. A. Lowe, T. J. Barton, and M. L. Tumey, *J. Am. Chem. Soc.*, 1976, **98**, 7844.
[29] Y. Maeda and K. U. Ingold, *J. Am. Chem. Soc.*, 1979, **101**, 837.

Table 1 *Arrhenius parameters for the thermal decomposition of diazirines*



R^1	R^2	*Conditions*	log *A*	*E*/kcal mol^{-1}	*Ref.*
Me	Me	4 mm	13.89	33.17	21
F	F	200 mm	13.1	32.20	18
Et	Et	10 mm	13.73	31.89	17
—$(CH_2)_4$—		7 mm	13.40	30.50	17
—$(CH_2)_5$—		5 mm	13.34	30.87	17
Me	Cl	4 mm	11.71	27.18	19
Me	Cl	50 mm diazirine and 300 mm perfluoropropane	14.14	31.07	19
Et	Cl	20 mm diazirine and 60 mm n-butane	13.99	30.45	20
Pr^n	Cl	10 mm diazirine and 20 mm butane	13.98	30.98	20
Pr^i	Cl	10 mm diazirine and 20 mm butane	14.01	30.59	20
Bu^t	Cl	4 mm	13.36	29.50	20
CCl_3	Cl	CCl_4	13.8	29.20	22
CCl_3	Cl	iso-octane	13.8	29.00	22
Ph	Br	cyclohexene	13.75	27.36	23
Ph	Cl	dimethyl sulphoxide	14.11	28.11	23
Ph	Cl	cyclohexene	13.87	28.00	23
p-$MeOC_6H_4$	Cl	cyclohexene	13.41	26.49	34
p-MeC_6H_4	Cl	cyclohexene	13.94	27.87	34
p-ClC_6H_4	Cl	cyclohexene	13.81	27.72	34
p-$NO_2C_6H_4$	Cl	cyclohexene	13.80	27.85	34
m-ClC_6H_4	Cl	cyclohexene	13.56	27.58	35
m-MeC_6H_4	Cl	cyclohexene	13.80	27.85	35
p-MeC_6H_4	Cl	acetic acid	13.81	27.61	35
Cyclopropyl	Cl	2 mm	14.76	29.83	36*a*
Cyclopropyl	Br	2 mm	13.70	27.58	36*a*
Cyclopropyl	Cl	cyclohexene	13.64	27.49	35
Cyclopropyl	Cl	cyclohexene	13.53	29.11	35
C_2H_3	Me	CCl_4	13.70	25.60	37
C_2H_3	Me	dimethyl formamide	13.60	25.40	37
C_2H_3	Me	ethanol	13.70	25.60	37
Bu^n	Ph	dimethyl sulphoxide	13.26	28.08	25
Me	Ph	dimethyl sulphoxide	13.45	28.50	25
MeO	Cl	MeOH	13.52	24.16	45
MeO	Cl	gas	13.06	25.26	45
$PhCH_2$	Cl	CCl_4	13.82	29.60	62*a*

100 mm, but at 100 mm it has virtually reached the high pressure limit. At 4 mm pressure an activation energy of 33.17 kcal mol^{-1} and a log A value of 13.89 were reported. The Arrhenius parameters for these compounds will be discussed (Table 1). Frey and Stevens favoured a mechanism involving a concerted elimination of N_2 in which dimethylcarbene is formed as an intermediate. The results of Bottomley and Nyberg,[30] and those of Frey and Stevens,[21] after adjustment to infinite pressure, fit a single Arrhenius line. Bottomley and Nyberg concluded that the transition state is considerably looser than the initial configuration, is non-cyclic, and is probably free radical in nature.

The gas-phase decomposition of difluorodiazirine was studied by Neuvar and Mitsch.[18,31] They found that the decomposition rate constant at a total pressure of 200 mm is $k = 10^{13.1}\exp(-32\,200/RT)\ s^{-1}$. Although the data do not reveal the mechanism, Neuvar and Mitsch nevertheless suggested a mechanism involving the transient existence of a diazomethane intermediate prior to loss of nitrogen.

Frey and Scaplehorn[17] from their study on 3,3-tetra-3,3-pentamethylenediazirine and 3,3-diethyldiazirine conclude that all the reactions are homogeneous and first-order, and probably unimolecular.

Bridge, Frey, and Liu[19] from their further studies on the decomposition of 3-chloro-3-methyldiazirine found that the products, vinyl chloride and nitrogen, are formed quantitatively in a first-order reaction. Substitution by a chlorine atom at C-3 resulted in a stabilization of 2 kcal mol^{-1}. Although the reaction mechanism was not clear, the authors favour a carbene intermediate. The exothermicity on the decomposition of 3-chloro-3-methyldiazirine was discussed and further examined by Archer and Tyler.[32] Frey and Liu[20] also studied the thermal decomposition of several chlorodiazirines. The rate constants were determined in the high pressure region and were shown to be kinetically first-order. The experimental evidence on the pyrolysis of chlorodiazirines indicates that a carbene is formed, which gives products by the concerted elimination of nitrogen.

Although kinetic data were available for the gas-phase decomposition of diazirines prior to 1970, none were recorded for decomposition in solution. In keeping with the growing interest in diazirines as a source of free carbenes, Liu and Toriyama[22,23] carried out investigations of in solution decomposition of diazirines to seek information about the nature of such strained ring systems.

The decomposition of 3-chloro-3-trichloromethyldiazirine[22] in carbon tetrachloride and iso-octane was investigated over the temperature range 75—115 °C. The only products were nitrogen and tetrachloroethylene. The rate was shown to be invariant in a variety of solvents. Similarly, decomposition of 3-chloro- and 3-bromo-3-phenyldiazirines[23] in several solvents gave nitrogen and the corresponding carbene. The carbene can either react with diazirine giving a dimeric product, or with the solvent cyclohexene to yield 7-chloro-7-

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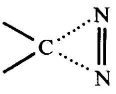
[30] G. A. Bottomley and G. L. Nyberg, *Aust. J. Chem.*, 1964, **17**, 406.

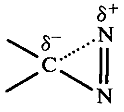
[31] R. A. Mitsch, *J. Heterocyclic Chem.*, 1964, **1**, 59; 1966, **3**, 245.

[32] W. H. Archer and B. J. Tyler, *J. Chem. Soc., Faraday Trans. I*, 1976, **72**, 1448.

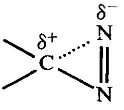
phenylnorcarane and the products of insertion at the C-3 and C-4 positions ($\sim$1 :1). This study indicates that the activation energy of 3-chloro-3-phenyldiazirine is lowered by $\sim$3 kcal mol^{-1} compared to that of 3-chloro-3-methyldiazirine. This difference may be attributed to the resonance stabilization afforded by the phenyl group on the transition state for diazirine decomposition. The value of the A factor of $\sim 10^{14}$ s^{-1} ($\Delta S^{\dagger} = +3$ cal K^{-1}mol^{-1}) is typical for a unimolecular reaction having a relatively tight transition state. As the rate of decomposition does not change with solvent polarity, the rate-determining step is likely to be radical rather than ionic. The fact that the Arrhenius parameters in the gas phase and in solution have similar values suggests that the transition state for all the diazirine decompositions is identical.[22,23] This conclusion is further corroborated by studies of the decomposition of 3-chloro-3-ethyldiazirine, in which the ratio $k_{\text{gas}}/k_{\text{cyclohexene}}$ has a value $10^{0.17}\exp(-0.85/RT)$.[33] Liu and Toriyama[34] examined the effect of *para* substituents on the thermal decomposition of a series of 3-chloro-3-aryldiazirines in various solvents. They found that the activation energies of 3-chloro-3-aryldiazirines and 3-chloro-3-alkyldiazirines are nicely explained by the different resonance stabilizations of the transition states I, II, and III. The observed effect of substituents on rates is in the following order: p-MeO > p-Me > p-Cl > H $\simeq$ p-NO$_2$. Transition state I was proposed by Frey *et al.*[19] to be the simplest case for diazirine decomposition. Schmitz[3] argued, however, that as the electron distribution on the carbon atom in transition state I must tend towards a sextet, it cannot be stabilized by electron withdrawal. If this were so, the order of the rates would be expected to be p-MeO > p-Me > H > p-Cl > p-NO$_2$, which is not in agreement with the observed results. Schmitz[3] has postulated instead an ionic transition state, II, as being more likely in view of the greater instability of α-ketopentamethylenediazirine with pentamethylenediazirine. If the reaction proceeds by transition state II, the rate should be: p-NO$_2$ > p-Cl > H > p-Me > p-MeO; unfortunately this order is the exact reverse of that observed. Finally, Liu and Toriyama[34] concluded that the best transition state is III. Experimentally, a Hammett correlation was determined for the series but it did not fit with either σ or σ^+ constants.[34] However, a smooth curve was obtained for all points except for the parent compound. On plotting log k *vs* $\sigma^+ - \sigma$ a straight line was obtained.[34] This result is in keeping with transition state III. Liu and Chien[35] examined the thermal decomposition of *meta*-substituted 3-chloro-3-aryldia-



I



II



III

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[33] M. T. H. Liu and D. H. T. Chien, *Can. J. Chem.*, 1974, **52**, 246.

[34] M. T. H. Liu and K. Toriyama, *Can. J. Chem.*, 1972, **50**, 3009.

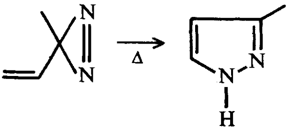
[35] M. T. H. Liu and D. H. T. Chien, *J. Chem. Soc., Perkin Trans. 2*, 1974, 937.

zirine and found that, in contrast to the *para*-substituted derivatives, the rates were linearly related to their respective σ values. Lower rate constants were also observed for the *meta*-substituted diazirines since the substituents are unable conjugatively to interact with the transition state. In fact, the data fall into two categories: (i) the *meta*-substituted derivatives (including the unsubstituted compound) and (ii) the *para*-substituents. The results are again consistent with a polarized, radical-like transition state III. The extent of the polarization depends on the diazirine ring substituent.

The thermolysis of 3-halo-3-cyclopropyldiazirines in the gas phase and in solution[36] give, respectively, nitrogen and 2-halobuta-1,3-diene and nitrogen and halocyclobutene, together with traces of the adduct from the cyclopropylhalocarbene and halocyclobutene. These results are conveniently interpreted in terms of vibrationally excited halocyclobutene molecules. In the gas phase, the excited halocyclobutene isomerizes completely to 2-halobuta-1,3-diene on account of its inherent instability. In solution, on the other hand, complete deactivation and consequently formation of the halocyclobutene occurs. In general, the activation energy for the bromo-compound is lower than that for the chloro-compound.[23,36]

The thermal decompositions of 3-chloro-3-cyclopropyl- and 3-chloro-3-cycloheptyldiazirine[35] in cyclohexene depend on the substituents. The rate constant for the decomposition of the cyclopropyl compound is an order of magnitude greater than for the diazirines containing cycloheptyl or alkyl substituents.

The most convincing argument for a step-wise mechanism (transition state III) is provided by the thermal isomerization of 3-methyl-3-vinyldiazirine.[37] Mainly 3-methylpyrazole is formed in a first-order isomerization in various solvents [equation (2)]. The fact that solvent effects and entropies of activation for the



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isomerization of 3-methyl-3-vinyldiazirine and 3-chloro-3-phenyldiazirine are similar points to a common transition state for both reactions. Since isomerization can only proceed by cleavage of a single C—N bond,[38] it can be concluded that the two C—N bonds in diazirine break consecutively. Although evidence is sufficient for a stepwise mechanism in the present case, it is not certain whether

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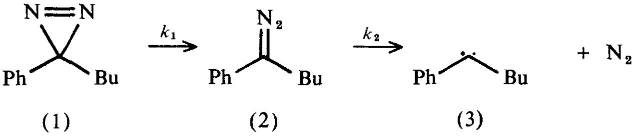
[36] W. J. Engelbrecht and S. W. J. Van Der Merwe, *J. S. African Chem. Inst.* (*a*) 1975, **28**, 144; (*b*) 1975, **28**, 148; (*c*) 1975, **28**, 158.

[37] M. T. H. Liu and K. Toriyama, *Can. J. Chem.*, 1973, **51**, 2393.

[38] An alternative pathway for this isomerization can be described since a concerted rearrangement such as a -1,3-sigmatropic shift (suprafacial for C-1, C-2, and C-3, antarafacial for N-1), not requiring the intermediacy of diazopropene is also possible. The possibility of such process is under investigation by M. T. H. Liu.

the intermediate is a radical or an ion. The small solvent effect observed has been discussed in terms of the compensation in net polarity of the diazo-intermediate.[37] The formation of diazomethane on thermal decomposition has always been inferred, since no diazomethane intermediate has ever been isolated from diazirine thermolysis.[34,35,39,40] Although an attempt to synthesize 3,3-diphenyldiazirine[41] resulted in the formation of diphenyldiazomethane, the precursory existence of a diazirine was never verified.

The first isolation of a diazomethane was reported by Jennings and Liu[24] for the case of phenyl-n-butyldiazirine (1) (Scheme 1). The thermal decomposition of (1) in dimethyl sulphoxide at 100 °C gave nitrogen and *cis*- and *trans*-1-phenylpent-1-enes (*cis* : *trans* = 1 : 5).



Scheme 1

The kinetic parameters[25] for the isomerization and decomposition in dimethyl sulphoxide of (1), k_1 and k_2, together with other experimental evidence showed that almost all diazirine (1) in dimethyl sulphoxide decomposes *via* the diazo-compound (2). The isomerization of phenylmethyldiazirine to 1-phenyldiazoethane is first order[25] and probably unimolecular, but the kinetics for the subsequent reactions of 1-phenyldiazoethane are complicated by several competing rate processes.[25,42] The distribution of azine and cyclopropane products depends on solvent polarities.[42] Azine arises from the dimerization of 1-phenyldiazoethane.[43] Bradley, Evans, and Stevens[44] found that cycloalkanespirodiazirines decomposed giving the corresponding cycloalkylidenes, which rearrange intramolecularly to cycloalkanes and bicycloalkanes. 3,3-Pentamethylenediazirine, on heating in acetic acid, yielded cyclohexyl acetate (23%) and cyclohexene (77%).[44] These findings permit the conclusion that cycloalkanespirodiazirines thermolyse by concurrent one- and two-bond cleavage.

Smith and Stevens[45] observed that 3-chloro-3-methoxydiazirines in the gas phase and in solution undergoes thermolysis regardless of the phase or the polarity of the solvent, in agreement with the result of Liu and Chien. The stabilization of the carbene centre by both chloro- and methoxy-substituents persuaded

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[39] E. Schmitz, C. Hörig, and C. Grundemann, *Chem. Ber.*, 1967, **100**, 2093.

[40] E. Schmitz, '23rd International Congress of Pure and Applied Chemistry' Vol. II, Butterworths, London, 1971, p. 283.

[41] C. G. Overberger and J.-P Anselme, *Tetrahedron Lett.*, 1963, 1405.

[42] M. T. H. Liu and K. Ramakrishnan, *J. Org. Chem.*, 1977, **42**, 3450.

[43] M. T. H. Liu and K. Ramakrishnan, *Tetrahedron Lett.*, 1977, 3139.

[44] G. F. Bradley, W. B. L. Evans, and I. D. R. Stevens, *J. Chem Soc., Perkin Trans. 2*, 1977, 1214.

[45] N. P. Smith and I. D. R. Stevens, *J. Chem. Soc., Perkin Trans. 2*, 1979, 213.

Smith and Stevens to favour a simultaneous two-bond rupture. The thermal decomposition of phenyl-n-butyldiazirine in the presence of *meta*-chloroperbenzoic acid (MCPBA) gave *cis*- and *trans*-1-phenylpent-1-ene oxides and valerophenone.[46,47] These products together with the kinetic data indicate that the oxidation does not take place on the diazirine ring, but rather that attack occurs on 1-phenyl-1-diazopentane.

To date, all the data suggest that either the carbenic or the diazo or both pathways for the thermal decomposition of diazirine depend on (i) the nature of the diazirine ring substituents, (ii) the stability of the intermediate diazo-compound, and (iii) the ability of the solvent molecules to stabilize the carbene or diazo-intermediate.

3 Photolysis of Diazirines

The mechanism of photolysis of diazirine is similar to that for thermolysis. However, because the energy of the light quanta are greater than the thermal energy of activation, the products contain excess internal energy which results in further decomposition or isomerization occurring.

A very detailed review on the photolysis of diazirines was prepared by Frey[6] in 1966. The early studies mainly concerned the nature of products and the chemical processes involved in their formation. The primary products are carbenes and molecular nitrogen. The resulting carbenes can be captured when saturated or unsaturated hydrocarbons are present. For example, the photolysis of 3*H*-diazirine in the presence of excess cyclobutane[48] yielded methylcyclobutane, ethylene, and propylene, whereas photolysis alone yielded ethylene and nitrogen. These observations were rationalized by Frey and Stevens who suggest that the mechanism involves the insertion of methylene to cyclobutane to give excited methylcyclobutane which is then deactivated or decomposes to give ethylene and propylene. The formation of ethylene when diazirine is photolysed alone is explained by the attack of methylene on diazirine.

Although the formation of diazomethanes as intermediates during the photolysis of 3-substituted diazirines is unquestioned,[6] their existence on photolysis of diazirine itself has been controversial. Amrich and Bell[49] photolysed 3*H*-diazirine in the gas phase under nitrogen using monochromatic light of ~ 320 nm. By monitoring the u.v. spectrum they detected the formation of diazomethane and they claimed that most of the excited diazirine decomposed to methylene and nitrogen while some isomerized to the excited diazomethane. The latter could either decompose to methylene and nitrogen or be stabilized by collision. From the quantum yields of products they concluded that about 20% of the primary decomposition of diazirine proceeds by isomerization to diazomethane.

These results are at variance with those of Moore and Pimentel[50] who carried

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[46] M. T. H. Liu and I. Yamamoto, *Can. J. Chem.*, 1979, **57**, 1299.

[47] M. T. H. Liu, G. E. Palmer, N. H. Chishti, *J. Chem. Soc., Perkin Trans. 2*, 1981, 53.

[48] H. M. Frey and I. D. R. Stevens, *Proc. Chem. Soc.*, 1962, 79.

[49] M. J. Amrich and J. A. Bell, *J. Am. Chem. Soc.*, 1964, **86**, 292.

[50] C. B. Moore and G. C. Pimentel, *J. Chem. Phys.*, 1964, **41**, 3504.

out the photolysis of diazirine in a solid nitrogen matrix. They detected diazomethane, but concluded from results using a ^{15}N matrix that it derived from the reaction of methylene with nitrogen.

In the case of 3-methyldiazirine,[51] Frey and Stevens considered that the diazirine molecule initially fragmented to ethylene and methyl carbene. The carbene could first rearrange to vibrationally excited ethylene, and then to acetylene and hydrogen. This mechanism predicts that at sufficiently low pressures the yield of acetylene will tend to 100%. However, a plot of acetylene yield as a function of pressure extrapolates only to 60.2%. Consequently there must be an additional reaction leading to ethylene which is incapable of decomposing to acetylene and hydrogen. They found no evidence for the isomerization to diazoethane during the photolysis.

Frey and Stevens later studied the photolysis and pyrolysis of 3-methyl-3-ethyldiazirine,[52] 3,3-diethyldiazirine,[53] 3-methyl-3-isopropyldiazirine, and 3-t-butyldiazirine.[54] The product ratios are different for the photolysis and pyrolysis reactions, which can be attributed to the formation of a 'hot' carbene in the photolysis reactions.

Difluorodiazirine on photolysis[55] using a medium pressure mercury arc lamp (GE-AH4) in inert matrices at 4—20 K generated CF_2 free radicals and N_2 as the principal products. On warming to 20 K they observed C_2F_4, undoubtedly derived from the recombination of free radicals. Irradiation of the same reactant in a cryogenic mass spectrometer[56] at $-139\,^{\circ}C$ gave small amounts of cyclic compounds, presumably from the addition of CF_2 to $F_2C{=}N{-}N{=}CF_2$.

The gas-phase photolysis of 3-chloro-3-methyldiazirine[57] gave vinyl chloride, acetylene, hydrogen chloride, 1,1-dichloroethane, and nitrogen. Photolysis with added hydrogen bromide led to the formation of 1-bromo-1-chloroethane. Clearly the formation of 1,1-dihalo-derivatives arise by the reaction of the intermediate carbene with hydrogen chloride.[57]

From the results of photolysis of 3-chloro-3-methyldiazirine,[58] Frey and Penny further argued that 1,1-dichloroethane arose from the reaction of methylchlorodiazomethane, formed by photoisomerization from diazirine with HCl.

Cadman *et al.*[59] from a study on the photolysis of 3-chloro-3-methyldiazirine favour a statistical distribution for the energy dispersion. Subsequently, Figuera and co-workers[60] questioned the validity of this statistical distribution and proposed a mechanism involving two pathways leading to vinyl chloride.

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[51] H. M. Frey and I. D. R. Stevens, *J. Chem. Soc.*, 1965, 1700.

[52] H. M. Frey and I. D. R. Stevens, *J. Am. Chem. Soc.*, 1962, **84**, 2647.

[53] A. M. Mansoor and I. D. R. Stevens, *Tetrahedron Lett.*, 1966, 1733.

[54] H. M. Frey and I. D. R. Stevens, *J. Chem. Soc.*, 1965, 3101.

[55] D. E. Milligan, D. E. Mann, M. E. Jacox, and R. A. Mitsch, *J. Chem. Phys.*, 1964, **41**, 1199.

[56] S. S. Cristy and G. Mamantov, *Int. J. Mass Spectrom. Ion Phys.*, 1970, **5**, 319.

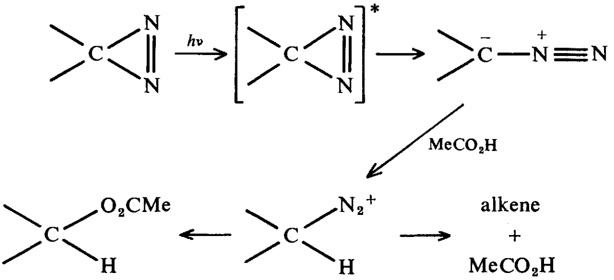
[57] W. E. Jones, J. S. Wasson, and M. T. H. Liu, *J. Photochem.*, 1976, **5**, 311.

[58] H. M. Frey and D. E. Penny, *J. Chem. Soc., Faraday Trans. 1*, 1977, 2010.

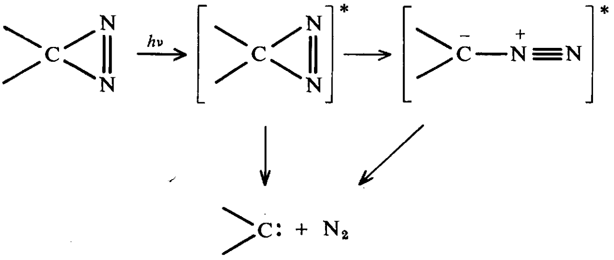
[59] P. Cadman, W. J. Engelbrecht, S. Lotz, and S. W. J. Van der Merwe, *J. S. African Chem. Inst.*, 1974, **27**, 149.

[60] J. M. Figuera, J. M. Perez, and A. Tobar, *J. Chem. Soc., Faraday Trans. 1*, 1978, 809.

In the gas-phase photolysis of pentamethylenediazirine,[61] the products are cyclohexene, bicyclo[3.1.0]hexane, methylenecyclopentane, butadiene, and ethylene. The mechanism proposed involves a carbene rearrangement generating a 'hot' species which decomposes unimolecularly or becomes deactivated by collision. Normally butadiene and ethylene arise by cycloreversion of excited cyclohexene; however, in the presence of a large excess of nitrogen, this process is virtually eliminated. In the liquid-phase photolysis of cycloalkanespirodiazirines, Stevens and co-workers[44] provided evidence for the formation of diazocycloalkane in the initial phases of the reaction. The photolysis of pentamethylenediazirine in acetic acid and in [^{2}H]acetic acid showed that 59% of the diazirine decomposed *via* the diazonium ion (Scheme 2) and the remaining 41% *via* the diazo-intermediate (Scheme 3). Accordingly, acetate resulted from the diazonium ion only whereas the alkene could arise from the diazonium ion or the carbene intermediate.



Scheme 2

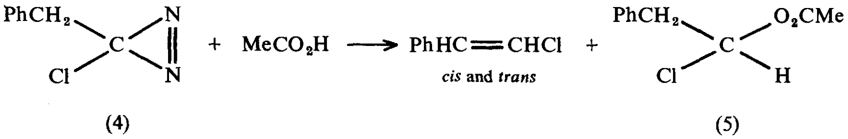


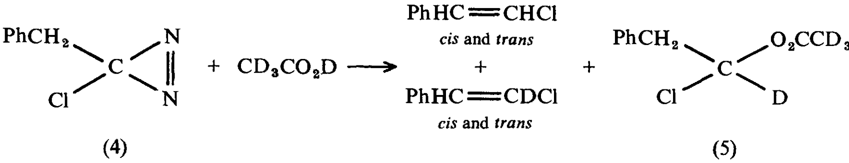
Scheme 3

Liu and co-workers[47] have further tested the validity of these schemes by conducting the photolysis of phenyl-n-butyldiazirine in acetic acid and [^{2}H$_4$]-acetic acid. They found that the photolysis of the diazirine in acetic acid proceeded only *via* Scheme 2, without any participation of the carbene intermediate (Scheme 3). In the thermal decomposition of phenyl-n-butyldiazirine at various

[61] H. M. Frey and I. D. R. Stevens, *J. Chem. Soc.*, 1964, 4700.

concentrations of acetic acid,[47] the alkene-acetate product ratio is insensitive to changes in acetic acid concentration, thereby suggesting that the products are derived mainly from the reactions of 1-phenyl-1-diazopentane. However, further work by Liu and Chishti[62a] on the photochemical decomposition of 3-chloro-3-benzyldiazirine (4) in acetic acid and [$^2H_4$]acetic acid supports a carbenic mechanism. The products of the chlorodiazirine were exclusively *cis*- and *trans*-β-chlorostyrene and 1-chloro-2-phenylethylacetate (5) according to equations (3) and (4).


(3)


(4)

The photolysis of (4) was also carried out at different concentrations of acetic acid in carbon tetrachloride. The alkene:acetate product ratio varied with the acetic acid concentrations. This result points to chlorobenzylcarbene as the key intermediate (Scheme 4).

Laser flash photolysis of 3-chloro-3-aryldiazirines in the presence of acetic acid at room temperature [62b] showed that the chlorophenylcarbene inserts into the O—H bond of the acetic acid[62c] with a quenching rate-constant $k_q \sim 2 \times 10^9$ M^{-1} s^{-1}. If the insertion of chlorobenzylcarbene into O—H bond of the acetic acid is assumed to be diffusion controlled, then the product concentrations indicate a rate constant of the order $\sim 10^8$ M^{-1} s^{-1} for the 1,2-hydrogen shift.

Revealing observations have been obtained from studies on diazirines as possible photo-affinity labelling compounds for biological systems.[63] Spectral evidence for the diazo-intermediate was forthcoming. Irradiation in acetic acid indicated that it underwent fragmentation to arylcarbene and photoisomerization to the linear diazo-compound.[63a]

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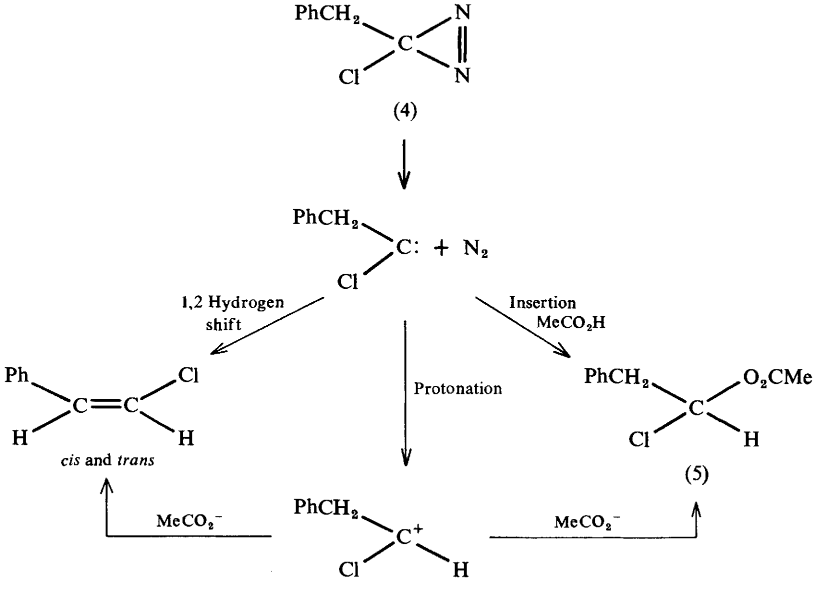
[62] (*a*) M. T. H. Liu and N. H. Chishti, to be published. (*b*) D. Griller, M. T. H. Liu, J. C. Scaiano, and P. C. Wong, to be published. (*c*) An alternative mechanism is the addition of the carbene to the oxygen lone-pair to form an ylide, which then gives product by O→C proton transfer. However, this mechanism is not in keeping with our laser flash photolysis experiments.

[63] R. A. G. Smith and J. R. Knowles, *J. Chem. Soc., Perkin Trans. 2*, 1975, 686; H. Bayley and J. R. Knowles, *Biochemistry*, 1978, **17**, 2420; J. Brunner, H. Senn, and F. M. Richards, *J. Biol. Chem.*, 1980, **255**, 3313; B. Erni and H. G. Khorana, *J. Am. Chem. Soc.*, 1980, **102**, 3888.



Scheme 4

Although the photochemical transformation of diazirines into diazo-compounds is feasible, the first example of the reverse process was only published in 1971. Lowe and Parker[64] showed that *N*-diazoacetylpiperidine on irradiation with visible light gave *N*-diazirinylcarbonylpiperidine in about 20% yield. Franich *et al.*[65] have also suggested that this photochemical isomerization is restricted to diazoamides, in which the excited state is stabilized by the amide group. Indeed, such isomerizations have been observed for a few linear[65] and cyclic[66,67] α-diazoamides. Similar isomerization of α-diazoketones was virtually unknown until 1978 when Mukai and co-workers[68] reported the reversible photochemical valence isomerization between α-diazoketones and α-keto-diazirines. The stabilization by the amide or π-bond participation has been invoked.[68] *Ab initio* SCF calculations on the photochemical behaviour of diazirine[69] are in general agreement with experiment.

4 Diazirine as a Source of Carbene

Few methods are available for generating 'free' carbenes as most methods

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[64] G. Lowe and J. Parker, *J. Chem. Soc., Chem. Commun.*, 1971, 1135.
[65] R. A. Franich, G. Lowe, and J. Parker, *J. Chem. Soc., Perkin Trans. 1*, 1972, 2034.
[66] E. Voigt and H. Meier, *Angew. Chem., Int. Ed. Engl.*, 1975, **14**, 103.
[67] E. Voigt and H. Meier, *Chem. Ber.*, 1975, **108**, 3326.
[68] T. Miyashi, T. Nakajo, and T. Mukai, *J. Chem. Soc., Chem. Commun.*, 1978, 442.
[69] B. Bigot, R. Ponec, A. Sevin, and A. Devaquet, *J. Am. Chem. Soc.*, 1978, **100**, 6575.

produce only carbenoids. Our understanding of the reactivity and spin states of carbenes has benefited significantly from studies of photolysis of diazirines. Photolysis of phenylbromodiazirine[70] in various alkenes gave essentially configurationally pure cyclopropane adducts. Additions to *cis*-butene were highly stereospecific. Methylchlorocarbene generated by the photolysis of 3-chloro-3-methyldiazirine[71] added to *cis*- and *trans*-butene giving the corresponding cyclopropanes in stereospecific manner. Photolysis of 3,3-difluorodiazirine[72] in alkenes also afforded stereospecific adducts, showing that the difluorocarbene is formed and is reacting as a singlet.

It is generally held that if a singlet carbene can undergo intramolecularly an internal insertion or cycloaddition it will not be efficiently trapped by an external reagent.[11] In contrast, Moss and Munjal[73] have shown that the carbenes formed by photolysis of 3-chloro-3-ethyl, 3-chloro-3-isopropyl, and 3-chloro-3-t-butyldiazirine added readily to external alkenes. Intermolecular addition was found to be far more efficient than intramolecular reaction for chloroethylcarbene and chloro-t-butylcarbene. The reverse trend was observed for chloroisopropylcarbene. It has been suggested that the stabilization of positive charge at the migration origin[74] is necessary for efficient 1,2-hydrogen shift. However, the thermolysis of 3-chloro-3-isopropyldiazirine[20] gave only 1-chloro-2-methylpropene. Moreover, the thermolysis of isopropyldiazirine[53] afforded nearly equal amounts of methylcyclopropane and isobutene. It follows that the chlorine atom disfavours C—H insertion.

Little attention has been lent to solvent effects on 1,2-hydrogen shift to divalent carbon generated from diazirines or diazo-compounds. The rate of thermal decomposition of 3-chloro- and 3-bromo-3-ethyldiazirine[33] is insensitive to the nature of the solvent, but the subsequent reactions of the carbene are affected.

Continuing their studies on capture of carbene by alkenes Moss and Fantina[75] photolytically generated cyclopropylchlorocarbene from cyclopropylchlorodiazirine and added it to a variety of alkenes. Additions to both *cis*- and *trans*-butene were stereospecific. Stabilizing factors such as the dual interactions of the chlorine lone-pair and the 'bent' σ-bonds of the cyclopropyl group have been invoked. The singlet carbene adopted the 'bisected' conformation which disfavoured the hydride migration. Cyclobutylchlorocarbene photolytically generated from the corresponding diazirine[76] was intercepted by a variety of alkenes accompanied by ring expansion and hydride shift products.

Although carbenes can be classified into two categories, electrophilic and

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[70] R. A. Moss, *Tetrahedron Lett.*, 1967, 4905.
[71] R. A. Moss and A. Mamantov, *J. Am. Chem. Soc.*, 1970, **92**, 6951.
[72] R. A. Mitsch, *J. Am. Chem. Soc.*, 1965, **87**, 758.
[73] R. A. Moss and R. C. Munjal, *J. Chem. Soc., Chem. Commun.*, 1978, 775.
[74] T. T. Su and E. R. Thornton, *J. Am. Chem. Soc.*, 1978, **100**, 1872.
[75] R. A. Moss and M. E. Fantina, *J. Am. Chem. Soc.*, 1978, **100**, 6788.
[76] R. A. Moss, M. E. Fantina, and R. C. Munjal, *Tetrahedron Lett.*, 1979, 1277.

nucleophilic, diazirines offer the mechanistically interesting possibility of giving 'ambiphilic' carbenes.[77,78]

5 Concluding Remarks

It is established that diazoalkanes are formed in the thermolysis and photolysis of some diazirines. It is to be expected that further investigation of the thermochemistry, for example, will resolve the many conflicting reports[9] concerning the value of $\Delta H_f{}^\circ$ for diazirine. Advances are also anticipated from the technique of laser flash photolysis. Use of alternative modes in inducing decomposition[79] are also to be envisaged. The low energy (5—20 eV) electron impact studies of 3-chloro-3-methyldiazirine by Kuwata and co-workers,[80] where $N_2(C^3\pi_u)$, $CN(B^2\Sigma^+)$, and $CH(A^2\Delta)$ are formed, look promising. The reaction of 3-chloro-3-methyldiazirine with hydrogen atoms, produced by microwave discharge, gave HCl and acetonitrile.[81] Here the activation of the methyl group is responsible for the reaction course.

In summary, recent years have witnessed extensive investigations into the thermolysis and photolysis of diazirines. Experiments have been performed in which intermediates have been trapped and by which mechanistic pathways have been elucidated. New compounds have been synthesized. As a result, diazirines, as a class, have become better understood.

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[77] R. A. Moss and W.-C Shieh, *Tetrahedron Lett.*, 1978, 1935.

[78] N. P. Smith and I. D. R. Stevens, *Tetrahedron Lett.*, 1978, 1931.

[79] K. T. Chang and H. Shechter, *J. Am. Chem. Soc.*, 1979, **101**, 5082.

[80] M. T. H. Liu, T. Tanaka, T. Hirotsu, K. Fukui, I. Fujita, and K. Kuwata, *J. Phys. Chem.*, 1980, **84**, 3184.

[81] C. D. Burkholder, W. E. Jones, J. S. Wasson, and M. T. H. Liu, *J. Am. Chem. Soc.*, 1980, **102**, 2841.