HETEROAROMATIC CARBENES (REVIEW)

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We correlate information on the chemistry of heteroaromatic carbenes. We consider methods for generation of electrophilic and nucleophilic heteroaromatic carbenes, their reaction pathways, and their role in organic synthesis.

In carbene chemistry, heteroaromatic carbenes occupy a special position due to their structural features and reactivity. As we know, in carbenes the carbon atom is covalently bonded to two substituents and contains two free electrons (s or p) whose spins can be antiparallel (singlet state of a carbene having an unoccupied p orbital) or parallel (triplet state of a carbene resembling a biradical). Carbenes in the singlet state, as species having simultaneously an unbonded electron pair and a free p orbital, can display (depending on the electronic nature of the substituents) both nucleophilic and electrophilic properties. A characteristic feature of the electronic structure of heteroaromatic carbenes is the fact that the carbene carbon atom participates with its own free pair or unoccupied p orbital in formation of a cyclic π-electron shell of the molecule. In the first case, we have electrophilic carbenes; in the second case, we have nucleophilic carbenes. Due to the stability of the aromatic electron shell, the nucleophilicity or electrophilicity of heteroaromatic carbenes is usually rather pronounced, and we more rarely encounter examples where heteroaromatic carbenes display mixed properties or a triplet character. Strictly speaking, such cases are known only for electrophilic carbenes.

Concerning nomenclature: For heterocyclic carbenes, usually we use the suffix -ylidene; and for electrophilic carbenes, as the base we take the aromatic ring (for example, azolylidene) while for nucleophilic carbenes we take the hydrated ring (for example, azolinylidene). Compounds which generate carbenes (carbene precursors) are appropriately called protocarbenes or carbenogens. The term "carbenoid" is used for complexes of carbenes, although it is also encountered in designating hetero analogs of carbenes, and also labile organometallic compounds capable of generating carbenes or their weak complexes in solutions [1].

We should note that since publication of the general papers [2, 3], there have been no specialized reviews in the literature on the problem of heteroaromatic carbenes. They are only fleetingly mentioned as illustrations or special cases of a specific cases of some point in the general chemistry of carbenes [1, 4].

ELECTROPHILIC HETEROAROMATIC CARBENES*

When exposed to light or heated, heteroaromatic diazo compounds generate electrophilic carbenes which *in situ* add to nucleophilic multiple bonds (the typical indicator of singlet carbenes [4]). Such thermal reactions and photoreactions are known both in the series of five-membered heterocycles (derivatives of pyrrole [5, 6], pyrazole [7-10], imidazole (11), triazole (12, 13], tetrazole [14, 15]) and six-membered heterocycles. A case of acid-base generation of electrophilic dihydropyridylidene from N-fluoropyridinium salt has been described in [16].

Analysis of the characteristic orientations of reaction of five-membered hetero systems in the carbene state, as highly electrophilic singlets, appropriately begins with conversions of 3H-pyrazolylidenes [8]:

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*Symbols for aromatic carbenes: (see next page)

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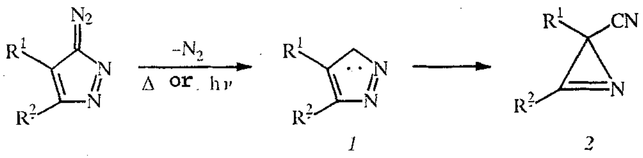
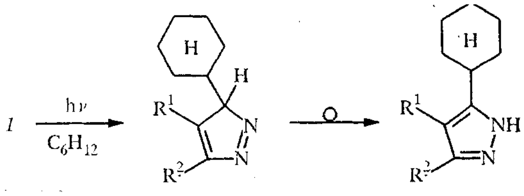
a. Isomerization of Carbene 1 to 2H-Azirine 2.

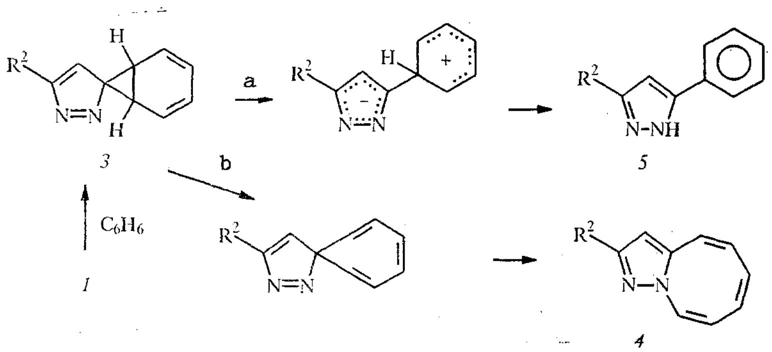


This type of reaction is characteristic only for pyrazolylidenes.

b. Capture of Carbene 1 by a Hydrocarbon Substrate by Insertion into a C−H Bond.



c. Addition of Carbene 1 at a Multiple Bond, such as to Benzene (Intermediate 3), Followed by Sigmatropic Rearrangement Processes.



In this case, as shown for pyrrolylidenes [6] and pyrazolylidenes [8], depending on the electronic nature of the substituents on the nucleophilic substrate, the result of the reaction may be different (pathway a or b). Electron-acceptor groups in the benzene component favor conversion of the spiro adduct with ring expansion (the yields of azocine 4 reach 50%). Electron-donor groups direct the conversion toward collapse with formation of the hydrogen substitution product in the original heteronucleus (the yields of phenylazole 5 are 40-90%). The primary spiro adduct is formed here by singlet carbene. The nature of the carbene considerably affects the orientation of the conversion: for benzene spiro adducts (derivatives of 1,2,4-triazolylidenes), expansion of the benzene ring is not characteristic, only the phenyl-substituted 1,2,4-triazole is isolated [13]. In the photosensitized reaction of decomposition of azopyrrole (for example, by the Michler ketone [5]), in contrast to thermolysis and photolysis, ring expansion is not observed; the route to the benzenated azole includes inversion of the initially formed triplet biradical to the singlet state followed by migration of the oxygen.

(continued)

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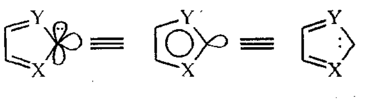
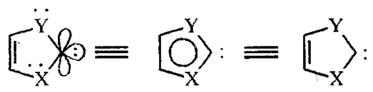
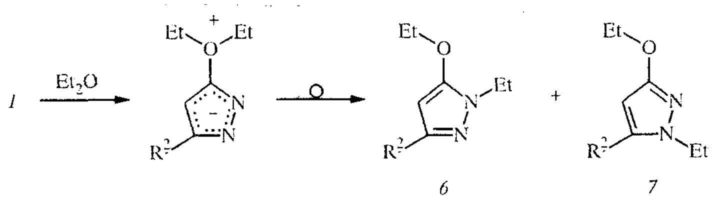


nucleophilic:



We must note that the reactions of addition of 1,2,4-triazolylidenes to benzene occur significantly faster than insertion at the C−H bond [13].

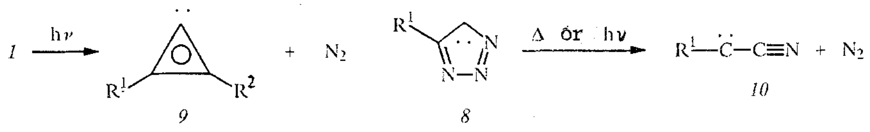
d. Cleavage of Ethers by Nucleophilic Attack by Carbene 1 at the Ether Oxygen Atom with Formation of 1,2- and 1,3-adducts 6 and 7 [9].



The considered reactions are rather general for azoles. For imidazolylidenes under conditions of photoreaction with alcohols, we observe not only addition at the oxygen atom with formation of ethers [11], but also insertion at the C−H bond, as a result of which we obtain the imidazolyl derivatives of the alcohols (yields 20-40%). The latter orientation of the reaction is due both to the high electrophilicity of the singlet carbene and obviously the fact that the C−H bond is weaker than the O−H bond.

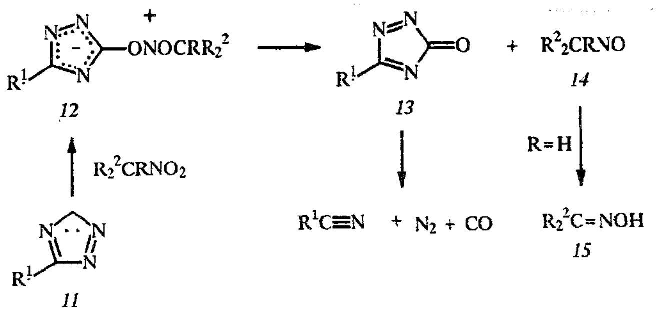
Reactions of electrophilic carbenes with alcohols under photolysis conditions for diazo compounds are not distinguished by selectivity, and along with formation of the compounds noted above, oxidation−reduction processes can also occur with participation of the heterocycle [11].

For electrophilic carbenes 1 and 8, intramolecular conversion to "secondary" carbenes 9 and 10 is known [8, 12].



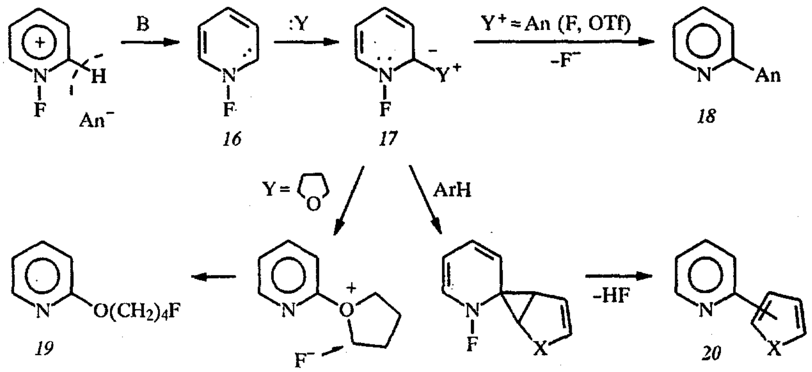
Upon reaction of 1,2,4-triazolylidenes with benzylidenetrifluoride, insertion at the C−F bond occurs.

The reaction of transfer of an oxygen to azolylidenes 11 from nitro compounds is of interest, occurring through the intermediate betaine 12 with formation of labile oxo derivatives 13 [13]. Under thermolysis conditions for diazo-1,2,4-triazoles, this reaction is accomplished with a number of nitro compounds and serves as a preparative route for synthesis of nitroso compounds 14 or oximes 15.



In [17], an *ab initio* estimate was made of the stability of electrophilic azolylidenes. Opening of the azole ring occurs spontaneously only when there are at least two nitrogen atoms, in the 2 and 3 positions of the ring.

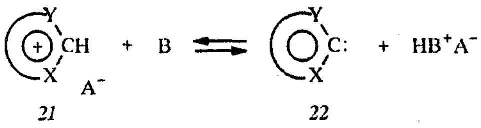
The dihydropyridylidene 16, substituted at the nitrogen atom by fluorine, in contrast to the methyl-substituted compound displays electrophilic properties, obviously due to the strong electron-acceptor effect of the fluorine. Such a carbene adds to the hydroxide ion and to alkoxides but not to amines, in a medium of which formation occurs (as a result of rearrangement in the carbenoid substrate 17) of 2-pyridyltosylates and 2-fluoropyridines 18 [16], or other derivatives (for example, compounds 19 and 20) if the carbene reacts with different nucleophiles.



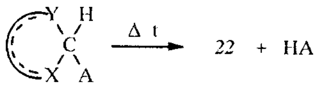
NUCLEOPHILIC HETEROAROMATIC CARBENES

Generation. Let us consider reactions which can be used to generate nucleophilic heteroaromatic carbenes *in situ.*

1. Reaction of heteroaromatic salts 21 containing a sufficiently mobile hydrogen atom (usually in the meso position of the heteronucleus) with bases [1-3, 18].



The ease of formation of carbenes 22, which are conjugated bases of the corresponding acid salts 21, of course depends on the mobility of the hydrogen atoms; such mobility can be estimated from their kinetic acidity in H–D exchange or, within a given series, from the chemical shifts in the PMR spectra. In 3,4-dimethyloxazoline [19], exchange of a hydrogen atom in the meso position occurs about 40 times faster than in the corresponding thiazolium salt: the sulfur atom in the ring in all cases decreases the acid properties of the hydrogen atoms compared with the effect of the oxygen atom, obviously as a result of the lower electronegativity. But in thiazolium salts, deuterium exchange occurs even without base catalysis, in an acid medium [20], in contrast to the basic form of the heterocycle. Generally in azolium salts the rate of hydrogen exchange (2H) is greater than in the corresponding azoles by about 10 orders of magnitude. Therefore the values of a $\tau_{1/2}$ cannot be measured for all the salts using PMR. The chemical shifts of these compounds strongly depend on the solvent: going from a low-polarity solvent to methanol leads to an upfield shift, while for azoles it is the reverse. Annelation of the heteronucleus with a benzene ring is manifested in retardation of H-exchange [21]. Electron-acceptor substituents, as should be expected, enhance exchange; electron-donor substituents weaken it [22, 23]. Replacement of the CH group in the ring by N leads to enhancement of exchange by several orders of magnitude (10^3-10^4 times) [21, 23, 24]. The effect of the functional substituents in the 3- and 5-phenyl radicals of thiazolium salts on the CH acidity follows the Hammett equation [25], and the effect is almost identical in both ring positions. In thiazolium salts, H–D exchange occurs 10^3-10^4 times faster than in the corresponding imidazolium analogs, and is faster than the rate of exchange in isothiazolium salts to a similar degree [23]. The exchange mechanism is considered in [26]. In dithiolium salts, the reaction halflife decreases with an increase in the inductive substitutent constant in the dithiolium nucleus. It decreases symbatically with the magnetic deshielding of the 2-position of the heteronucleus [27, 28]. In 1,3-disubstituted tetrazolium salts, replacement of the N-alkyl group by an N-aryl group accelerates exchange [29, 30]. The kinetic CH-acidity decreases considerably going from 1,4-disubstituted tetrazolium salts to the corresponding 1,3- and especially to the 2,3-disubstituted isomers [31]. In the pyridinium cation, the protons in the α-position undergon exchange most easily [32, 33]. The nature of the anion exerts a substantial effect on the ease of carbene formation in the salts. If the anion is a very weak nucleophile, for generation of the carbene state in the heterocycle we need to use a strong base like tertiary amines, mesitylmagnesium bromide, sodium triphenylmethanolate in aprotic solvents. If anion (A) is sufficiently nucleophilic, the salt can be a pseudobase 23, which can yield carbene 22 upon heating (A = CCl_3, OAlk, CN) [34].



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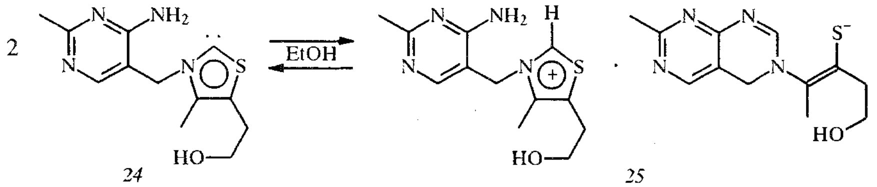
The thiazolinylidenium system (in thiamine) was the first heterocycle demanding the concepts of the heteroaromatic carbene state: Breslow turned the attention [35] of chemists to the high mobility of the meso hydrogen atom in thiazolium salts, in particular in thiamine, and defined the "ylide" formed as the resonance form of the heteroaromatic carbene 24. Relatively recently [36, 37], the carbene form of thiamine was isolated (by action on the latter at −10°C of an equimolar amount of sodium ethanolate in ethanol) in the form of a hygroscopic colorless material, stored under nitrogen atmosphere; in solution an equilibrium between the carbene form of thiamine 24 and the ion pair 25 is hypothesized.



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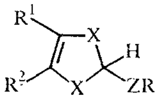
We should note that the first report of isolation of stable benzothiazolinylidene [38] was after review of [34, 39]. Nevertheless, recently it has been reported that a stable derivative of imidazolinylidene has been obtained in which the carbene center is sterically hindered by adamantyl substituents at both nitrogen atoms [40]. Generation of carbenes from carbenogenic salts (thiazolium, benzthiazolium, benzoxazolium, dithiolium), depending on their nature, occurs upon heating in triethylamine at room temperature in aprotic polar solvents (acetonitrile, DMSO) in the presence of triethylamine or other tertiary amines; by action of sodium hydride in dioxane; upon boiling in acetone in the presence of triethylamine; at 0°C in DMF in the presence of triethylamine [39]; by action of tert-butyllithium [31]. The processes are carried out under an inert atmosphere.

2. A useful source of carbenes is mesoalkoxy- and mesoamino-substituted dioxolenes, dithiolenes, imidazolines, oxazolines, thiazolines, and their benzo derivatives [41-43]. Carbenogens 26 can generate carbenes of type 22 in acid media, in contrast to the analogous salts.



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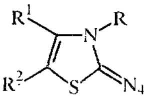

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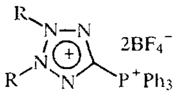

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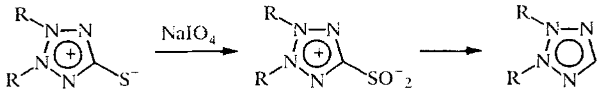
3. Thermal decomposition of 2-tetrazobenzothiazolines 27, which occurs under very mild conditions (~0°C) [44], yields benzothiazolinylidenes.

4. Generation of tetrazolinylidenes by F-induced dephosphoniation of the double 5-phosphoniotetrazolium salt 28 by action of cesium fluoride [31].

5. The same carbene is also formed upon hydrolysis of the above-mentioned salt.

6. Generation of tetrazolinylidenes 29 by oxidation of tetrazolium-5-thilate 30 [31].



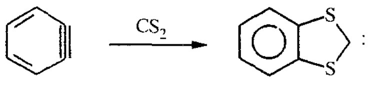
30 29

7. Nucleophilic heteroxanthenylidenes are formed upon photolysis of diazoheteroxanthenes [45].

8. Betaines (2-pyridinium, 2-quinolinium, 1-isoquinolium carboxylates) upon heating (40-80°C) in aprotic solvents abstract carbon dioxide with formation of the corresponding dihydroazinylidenes [46, 47].

9. Heteroaromatic carbenes are also formed upon reaction of bis-ylidenes with electrophilic reagents [34].

10. Benzdithiolenylidenes 31 are formed in reactions of dehydrobenzenes obtained by various methods with carbon disulfide [48-50].



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REACTIONS OF NUCLEOPHILIC HETEROAROMATIC CARBENES

In reactions in which nucleophilic heteraromatic carbenes are generated, in contrast to electrophilic carbenes, we do not observe formation of biradical isomers. They are characterized by a short lifetime, which determines a number of characteristic features of the reaction.

Reactions of nucleophilic heteraromatic carbenes have been the best studied in the series of five-membered systems, but such reactions are also known for azines and heteroxanthenes.

Reactions with Chalcogens. Heteroaromatic carbenes are quite sensitive to oxygen, with which they form "one" compounds. (Therefore all the operations which are not connected with directed synthesis of "ones" should be carried out under an inert gas atmosphere.) Thus upon action on the 1,3-diphenylimidazolium salt by potassium tert-butylate in DMSO, the corresponding imidazolone is formed [51], while 1,3,4-thiadiazolium salts in reactions with nucleophiles in the presence of air also form the corresponding 1,3,4-thiadiazolones [52]. Upon photolysis of heterodiazoxanthenes, we obtain heteroxanthones or, when ethylenes are present in solution as traps, the corresponding spiro-oxetanes [45].

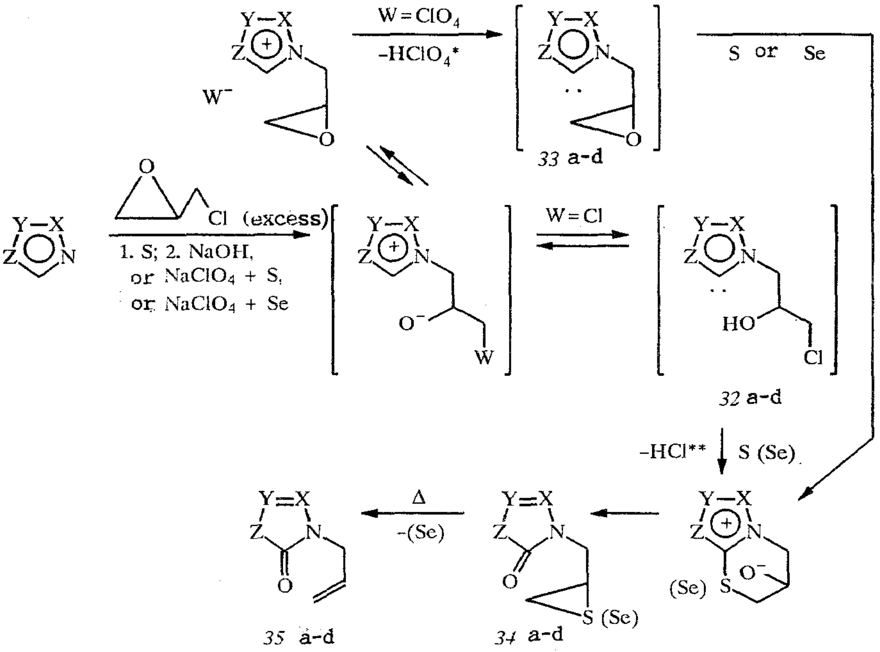
Reactions of carbenogenic salts with sulfur in the presence of bases with formation of the corresponding thiones is very characteristic and can serve in most cases as an indicator of carbene formation. Imidazolium [53], triazolium [54], and benzthiazolium [55, 56] salts at room temperature or upon boiling in pyridine form thiones in good yield. For imidazolium salts, we note that all other conditions being equal, the yield of thiones increases as the mobility of the meso proton increases, which corresponds to an increase in the downfield shift of the signals from the meso protons in the PMR spectrum (in DMSO-D_6) [51].

The carbene route has proven to be appropriate for synthesis of 2-thiocaffeine [57]. Under analogous conditions, upon boiling benzthiazolium salts in pyridine with metallic selenium we obtain the corresponding selenones [58, 59]. Upon heating (200-300°C) dithiobixanthylene, biflavenylene, dithiobiflavenylene, N,N-dimethylbiacridene with sulfur, we obtain the corresponding thioketones, through intermediate carbene formation [60]. The corresponding thiones are also formed when carbenes are generated in the presence of sulfur upon thermal decomposition of tetrazobenzothiazolines [61].

N-(2,3-epithiopropyl)-substituted azolones 34 are synthesized from azoles through carbene intermediates 32 and 33 [62]. In the presence of selenium, the end products of this reaction are N-allyl derivatives of azolones 35.

Formation of Bis-Ylidenes. Heteroaromatic carbenes 22 can form the bis-ylidenes 36, and this is one of the most characteristic reactions for them. Bis-ylidenes 36 are formed in different carbene generation reactions: from heteroaromatic salts 21 in the presence of bases [40, 43, 63-65], upon heating with acetic anhydride [66], upon thermolysis of mesoalkoxy-substituted 23 or (in acid medium) 2-amino-substituted five-membered heterocycles: derivatives of dioxolanes [41], dithiolanes [42, 43], thiazolines [34, 52, 61]. At the same time, an attempt to obtain bis-benzimidazolinylidenes proved to be unsuccessful [51]. Upon photolysis of diazoheteroxanthenes, the corresponding bis-ylidenes are also isolated [45].

First it was found that bis-ylidenes are formed directly as a result of combinations of two carbene particles 22, but it soon became clear that in any case this is not the only and evidently not even the major route for their synthesis in different carbene generation reactions. Carbenes 22, which are very active particles, at the moment they are generated can insert



32 — 35 a X+Y = C(CH=CH)$_2$C, Z = NCH$_3$; b X = Y = CC$_6$H$_5$, Z = NCH$_3$; c X = Y = CH, Z = NCH$_3$; d X+Y = C(CH=CH)$_2$C, Z = S

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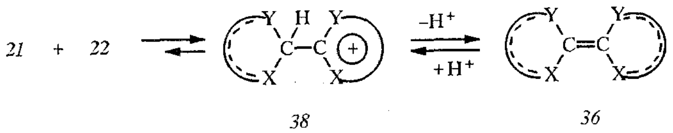
*Acceptor—base; **Acceptor-epichlorohydrin (excess).

themselves into a C–H bond [56] of the starting carbenogen, which is generally a strong electrophile whose concentration (in contrast to the concentration of the carbene formed in the rate-limiting step) is relatively high at the beginning of the reaction [61]. Therefore the reaction of combination of the two carbenes has insignificant weight in the general scheme for obtaining bis-ylidenes. Just such a course for the reaction is confirmed by the fact that, as was shown for the examples of dithiolium salts [42], under the action of alcoholates they are capable of combination, while the 2-alkoxy derivatives of dithiolanes no longer dimerize (i.e., we need a source of carbenes which also insert into the C–H bond of the substrate). Furthermore, under very mild conditions (almost at room temperature) for thermal generation of carbenes from 2-tetrazo-X-benzo[d]thiazolines, quite ideal conditions, when besides the starting compound other active components of the reaction are absent, dimers of type 36 are not detected in appreciable amounts [61]. It was also found that thermal dissociation of bis-ylidenes 36 into individual carbenes does not occur, as was suggested at first in [38], since upon heating a mixture of the two different dimers we do not observe formation of mixed bis-ylidenes [34].

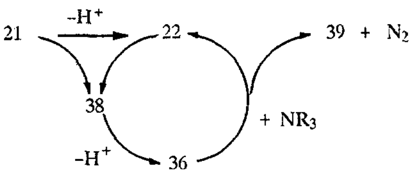


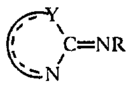
Reactions with Water. Heteroaromatic carbenes easily add to water [51] and, in this case, most often undergo ring opening [60, 67].

Reaction with Nitrogen-Containing Multiple Bonds. For the example of reactions of benzthiazolinylidenes with azides, it has been shown that, depending on the structure of the azides (determining their electrophilicity), we obtain either the products of capture of the azides (RN_3) by the carbene 22 (the corresponding triazacyanines 37) if the azide is strongly electrophilic (like 2-azidobenzothiazolium salts), or if the activity of the azide is low (like sulfazides, benzazides), the carbene 22 formed can be converted to bis-benzothiazolinylidene 36 with an electrophilic starting salt 21. Compound 36, reacting with the azide (RN_3), then yields the imine 39 and again generates carbene 22 and triazacyanine 37 [34, 68, 69]. Thus if RN_3 is strongly electrophilic, then:

$$21 \xrightarrow{-H^+} 22 \xrightarrow{RN_3} 37$$

If RN_3 is weakly electrophilic, then:





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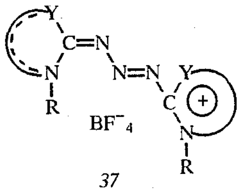
Carbenes generated from 2-tetrazobenzothiazolines with an excess of the latter yield tetrazenes 40; with azides, they yield triazocarbocyanines 37; with diazonium salts, the azo compounds 41; with diazo compounds, the diazines 42 [61, 70, 71]. Side reactions are also characteristic for dihydroazinylidenes generated upon thermal decarboxylation of pyridinium, quinolinium, and isoquinolinium 2-carboxylates [45, 72, 73].



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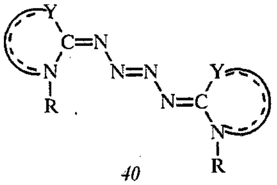

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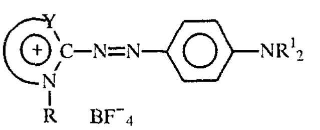

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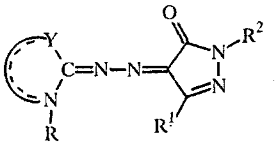

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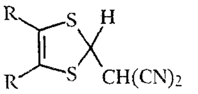
Insertion at CH or NH Bonds. Benzthiazolinylidene, generated from a salt, can insert itself into mobile C–H bonds [59, 74]. Dithiolenylidenes obtained *in situ* from various sources easily react with CH-acids of the RCHXY type [75, 76], forming the corresponding derivatives 43, 44. In the case when a carbene center and an active CH bond are present in the same molecule, as is the case in N-allylbenzthiazolin-2-ylidene, dimerization cyclization occurs [56] (compound 45).



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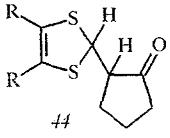

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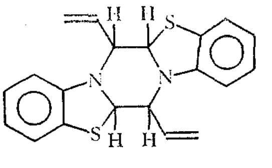

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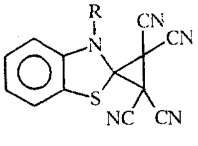
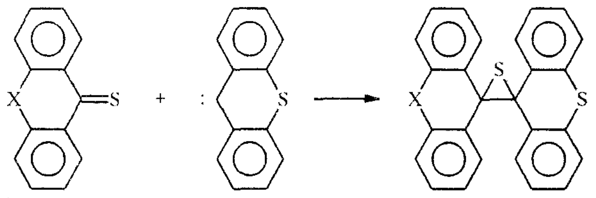


46

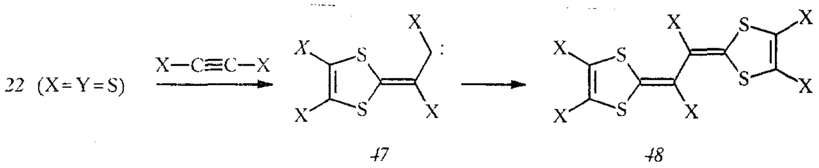
1,3-Dithiolenylidenes generated *in situ* from 2-methoxy-1,3-dithiolenes in the presence of acid yield 2-succinimido derivatives by means of insertion into the N–H bond [77] of the succinimide.

Thiazolinylidene generated in the thiamine molecule by action of triethylamine easily inserts itself into the N–H bond of amines [78]. Carbenes can yield adducts with tertiary amines, which have been detected in the case of thiazolinylidenes [79].

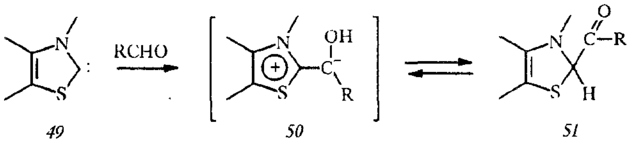
Addition at a Multiple Bond. Heteroaromatic nucleophilic carbenes, due to their electron-donor nature, do not react with trivial carbene traps of the cyclohexene type. But benzothiazolinylidenes yield adducts with substrates containing electron-deficient multiple bonds [61]. The presence of such compounds in the reaction medium leads to addition products 46, but only when the electrophile is sufficiently strong and able to compete with the carbenogen, which generally has electron-deficient centers and so self-condensation products 40 also appear. Addition of xanthenylidenes generated from 9-diazo-substituted derivatives to the thione bond yield spiro-thiiranes [80].



Reaction of carbene 22 with an electron-deficient triple bond leads to transfer of the carbene center to the side chain in the intermediate 47 and, when active electrophilic traps are present in the reaction medium, to formation of the corresponding adducts 48 [81, 82].

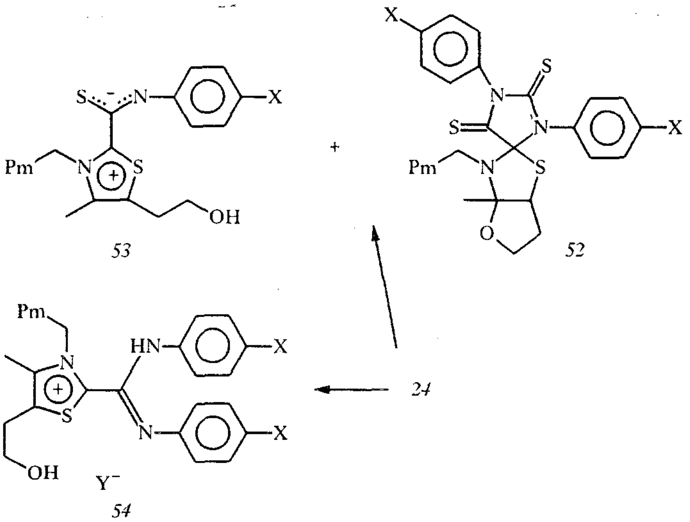


Reaction with Carbonyl Bonds. Heteroaromatic carbenes 49 (derivatives of benzthiazole, thiazole) add at the carbonyl bond (intermediate 50) and can yield products of insertion at the aldehyde group 51 [72, 83, 84].



The process is an equilibrium one; its orientation depends considerably on the nature of the carbene [85]. For N-amido-containing derivatives of triazolinylidenes, intramolecular carbene cyclization at the carbonyl group has been described [86].

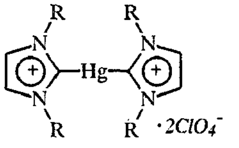
Reaction with Isocyanates, Isothiocyanates, Carbodiimides. Thiazolinylidenes [79], 1,3,4-thiadiazolinylidenes [87] with phenylisothiocyanates easily yield a spiro compound of type 52, formed through 1:1 dipolar adducts 53, which however have not been isolated in the case of isocyanates.



At the same time, 1:1 dipolar adducts of type 53 are obtained in the reaction of isothiocyanates in the absence of oxygen with imidazolinylidenes [51, 53], annelated by triazolinylidenes [69], thiazolinylidenes [88]. The same thiazolinylidene adds to a carbodiimide, but salt 54 is formed [88] due to the high basicity of the carbodiimide moiety. Benzthiazolinylidene has higher selectivity than the acyclic hetero analog in the reaction with phenylisothiocyanate, but the selectivity of this heteroaromatic carbene in the reaction with arylisocyanates was found to be that same as for the nonaromatic models in [89].

Reactions with Mercury Salts. Imidazolinylidenes formed *in situ* upon action of mercury acetate in DMSO on imidazolium perchlorates easily yield perchlorates of imidazoliummercury acetates or diimidazoliummercurates 55 [51, 53].

Reactions with Phosphorus Compounds. Phosphines serve as carbene traps. 4,5-Benzo-1,3-dioxolenylidene, generated upon heating 2-ethoxy-4,5-benzo-1,3-dioxolane, under an argon atmosphere forms adduct 56 with triphenylphosphine [41].



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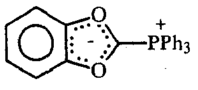

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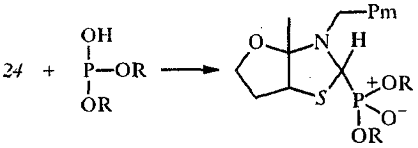
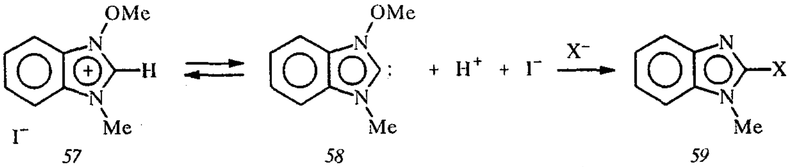


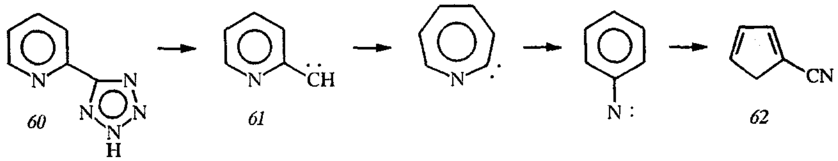
Upon reaction of thiazolinylidene 24 with phosphites, the Arbuzov rearrangement occurs [90].

Reaction with Haloalkyl Functional Groups. Alkylation and phenacylation of the thiazolinylidene unit in thiamine leads to its cycloconversion [37, 91].

Other Conversions. The very interesting conversion of nucleophilic heteroaromatic carbenes to electrophilic carbenes has been described for the example of the N-methoxy-N-methylbenzimidazolium salt 57 [92]. This salt in basic medium initially generates carbene 58 which, under the action of strong nucleophiles, reacts as an electrophilic species with simultaneous ejection of the methoxide dianion and formation of the 2-substituted benzimidazole 59. Potassium cyanide, sodium hydroxide, alcoholates, amines, hydrazine, CH-acids, and methylmagnesium iodide react in this way.



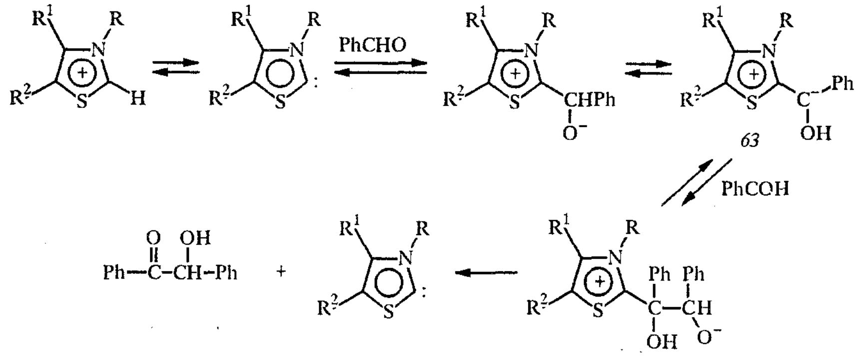
Carbenes in Gas-Phase Thermolysis of Aromatic Nitrogen Compounds. Upon thermolysis (~600°C; 0.05 mm) of 5-pyridyltetrazole 60, the pyridylcarbene 61 is formed, which as a result of successive recyclizations generates aromatic carbenes, ultimately being converted preferentially to cyanocyclopentadiene 62 [93].



Pyrolysis of ν-tirazolo[1,5-*a*]pyridine yields triplet nitrene, which in recyclization conversions (where the intermediates are tropylenylidenes but with spin conservation) are converted to azine, which is the characteristic product of such a reaction scheme [94].

A number of other examples of pyrolytic formation and conversion of carbenes and their interpretation are given in [95-102].

Catalysis of Benzoin Condensation. Breslow first turned the attention of chemists to carbene catalysis (using thiamine) of benzoin condensation [35], where the role of the catalyst involves formation of the so-called active aldehyde 63.

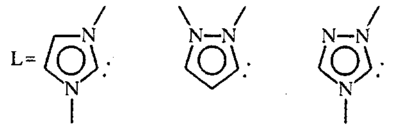


The catalytic action of thiamine has been investigated in many papers [103-107]. Such action is displayed not only by other thiazolium, imidazolium, and benzimidazolium salts [35]. The catalytic activity of thiazolium salts is substantially affected by the nature of the N-substituent [108]. Ethylbenzthiazolium bromide catalyzes formation of triose in the presence of base with high selectivity [109]. High activity of podand carbene structures has been observed [110]. Dithiolenylidenes exert a catalytic effect on isomerization of maleates [111, 112]. In addition to benzoin condensation, "formation condensation" of formaldehyde under the action of thiazolinylidene has been described. A characteristic feature of this condensation involves the fact that unbranched carbons are formed, although concatenation higher than C_6 is generally not achieved as a result of the reduction in reactivity of the "active aldehydes" as the chain length increases [113].

Complexes of Azolinylidenes with Heavy Metals. Complexes of azolinylidenes with transition metal carbonyls have been described [114]:

$$2\,[L\text{-}H]^+ + [M_2(CO)_{10}]^{2-} \longrightarrow (L\text{-}H)_2[M_2(CO)_{10}] \xrightarrow{-H_2} 2\,M(CO)_5L$$

$$2\,M(CO)_5L \longrightarrow M(CO)_6 + M(CO)_4L_2$$



M = Cr, Mo, W

From this review we can see how rich is the chemistry of heteroaromatic carbenes. In contrast to ordinary carbenes, in heteroaromatic carbenes either electrophilic or nucleophilic properties are pronounced, which formally reflects their aromatic nature according to the Hückel rule, and only in rare cases do we observe a change in the philicity of these carbenes. Unfortunately, their physical chemistry is still not very developed. For example, it is difficult to assess the quantitative correlation between the aromatic properties of these species and their carbene reactivity. At the same time, in the series of heteroaromatic carbenes, it has been possible (relatively recently) to isolate in the pure state rather stable carbene forms [36, 37, 40, 115]. Steric protection of the carbene center on the ring by substituents on the neighboring nitrogen atoms, like electronic stabilization as a result of the effect of electronegative hetero atoms in the nucleus, create appreciable kinetic passivity in the carbene. Such carbenes remain rather stable in the absence of oxygen and mixture.

X-ray diffraction data for N,N′-diadamantyl-substituted imidazolinylidene [40] show that the carbene angle in the heteronucleus is sharper than those in the analogous salt [$\theta(N_{(1)}C_{(2)}N_{(3)}$ 102.2° and 109.7° respectively], while the C−N bonds are slightly longer [$r(C_{(2)}-N_{(1)}$ 136.7 and 132.8 nm, $r(N_{(1)}-C_{(5)}$ and 137.8 nm respectively].

π-Delocalization in the carbene heteronucleus, according to quantum chemical calculations in [115], is less pronounced than in the cation, which is also consistent with the paramagnetic shift for the protons of the imidazole ring upon transition to the carbene state (δ 7.92 → 6.91 ppm). The good agreement between the experimental and theoretical values of the geometric parameters specifically for the singlet, together with the calculated value of the dipole moment (2.90 D), the $C_{(2)}$ wave function (close to that for the carbon center in a typical carbene $:CF_2$), the magnitude of the charge on the $C_{(2)}$ atom confirm the singlet carbene character, at least for imidazolinylidene, eliminating the ylide structure with separated charges.

We should turn our attention to the synthetic possibilities following from the chemistry of heteroaromatic carbenes. The reactivity of carbenes, especially nucleophilic carbenes, is more selective, which of course is important for organic synthesis. Here good sources open up for obtaining in particular azole systems functionally substituted at the meso position, their epoxide and thiirane monomers. Obviously analogous syntheses can become accessible also in a number of other heterocyclic systems: azines etc. Acyloin syntheses with participation of heteroaromatic carbenes as catalysts are promising. The chemistry of their complex compounds is enticing, since its possibilities have still hardly been investigated.

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