Russian Chemical Reviews **80** (11) 1035 – 1066 (2011) © 2011 Russian Academy of Sciences and Turpion Ltd

DOI 10.1070/RC2011v080n11ABEH004254

Transformations of diaziridines and their fused analogues induced by electrophilic reagents †

N N Makhova, A V Shevtsov, V Yu Petukhova

Contents

I.	Introduction	1035
II.	Reactions of diaziridines with protic and Lewis acids	1036
III.	Alkylation of diaziridines	1038
IV.	Reactions of 1- and 1,2-unsubstituted diaziridines with carbonyl compounds	1039
V.	Mannich reaction involving diaziridines	1040
VI.	Reactions of diaziridines with activated unsaturated compounds	1042
VII.	Reactions of diaziridines with acylating agents	1049
VIII.	Reactions of diaziridines with heterocumulenes	1054
IX.	Reactions of diaziridines with transition metal salts	1060
X.	Conclusion	1064

Abstract. The review deals with transformations of mono- and bicyclic diaziridine derivatives with different types of substitution induced by electrophilic reagents (protic acids, Lewis acids, alkylating and acylating agents, carbonyl compounds, heterocumulenes, activated alkenes and alkynes and transition metal salts). The characteristic features of the reactions are considered as functions of the structures of the starting diaziridines and the nature of the reaction medium (organic solvents, ionic liquids). Prospects of the use of diaziridine derivatives as readily available precursors for the synthesis of various nitrogen-containing heterocyclic systems based on the diaziridine ring expansion reactions are considered. The bibliography includes 136 references.

I. Introduction

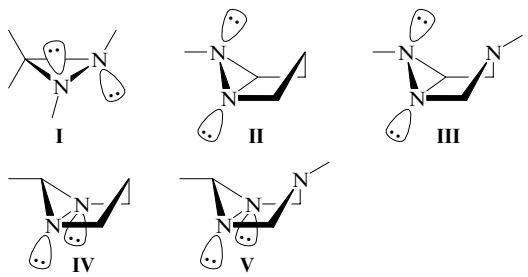
Diaziridines are saturated three-membered heterocyclic compounds with two nitrogen atoms (cyclic hydrazines). They were independently discovered by three research groups in 1958 – 1959, and considerable progress in the chemistry of these compounds was made in the next two decades after the first publications. During this period of time, some transformations of diaziridines induced by electrophilic reagents were found. The possibility of performing these reactions is associated primarily with the steric strain of the diaziridine ring and the presence of two nitrogen atoms. Information on the reactions of both mono- and bicyclic diaziridine-containing heterocyclic systems was summarized in several reviews [1–6] and in the monograph by E Schmitz,[7] who extensively investigated the chemistry of diaziridines and other three-membered heterocycles with two heteroatoms. However, these reviews included not only the reactions of diaziridines with electrophilic reagents but the whole chemistry of these compounds. Meanwhile, these transformations of readily available diaziridines under the action of electrophilic reagents producing reactive intermediates provide a simple route to a wide range of both practically significant linear compounds (for example, of hydrazines) and four – seven-membered heterocyclic systems, including those previously unknown.

The present review summarizes the reactions of electrophilic reagents with monocyclic diaziridines containing one, two, three or four substituents in the ring and their fused analogues, *viz*., 1,5- and 1,6-diazabicyclo[3.1.0]hexane and 1,3,5- and 1,3,6-triazabicyclo[3.1.0]hexane derivatives. The reactivity of diaziridines toward electrophilic reagents strongly depends on the orientation of the nitrogen lone pairs. Under usual conditions, the lone pairs (LP) (and substituents) in monocyclic diaziridines (**I**), as well as in 1,6-diaza- (**II**) and 1,3,6-triazabicyclo[3.1.0]hexanes (**III**), are in *trans* positions (the inversion barrier is 20 – 28 kcal mol^{-1}), whereas LP in 1,5-diaza- (**IV**) and 1,3,5-triazabicyclo[3.1.0]-hexanes (**V**) are in *cis* positions.

N N Makhova, A V Shevtsov, V Yu Petukhova N D Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Leninsky prosp. 47, 119991 Moscow, Russian Federation. Fax (7-499) 135 53 28, tel. (7-499) 135 53 26, e-mail: mnn@ioc.ac.ru (N N Makhova), a27@yandex.ru (A V Shevtsov), pvyu@ioc.ac.ru (V Yu Petukhova)

Received 11 July 2011
Uspekhi Khimii **80** (11) 1087 – 1118 (2011); translated by T N Safonova

† Dedicated to Academician O M Nefedov on the occasion of his 80th birthday.

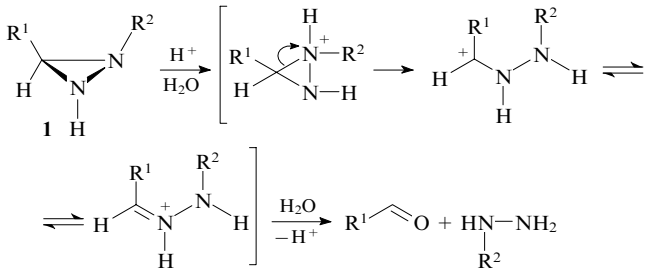


The present review considers transformation of diaziridines and their fused analogues induced by electrophilic reagents, which were discovered in the last 20–25 years (~70% references), although, if required for the completeness of the description, the results of earlier studies are included, in particular, the works of the research group headed by Professor R G Kostyanovsky dealing with different procedures for the separation of racemic diaziridines into enantiomers, which were not available in earlier reviews. Protic and Lewis acids, carbonyl compounds (including aminomethylation reactions with their participation), alkylating and acylating agents, heterocumulenes (ketenes, isocyanates and isothiocyanates), activated alkenes and alkynes, and some other reagents, including transition metal salts, are considered as electrophilic reagents.

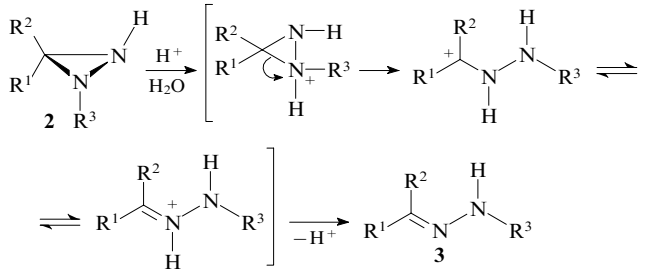
II. Reactions of diaziridines with protic and Lewis acids

Alkylated diaziridine derivatives and their fused analogues are prone to undergo acid-induced ring opening. The reactions of diaziridines with acids (see the reviews [1–7]) may be accompanied by either the C–N or N–N bond cleavage to form hydrazine and hydrazone derivatives (diaziridine–hydrazone rearrangement), as well as amines and carbonyl compounds. Several examples of the most typical transformations of diaziridines induced by protic and Lewis acids depending on the structure of the starting diaziridine derivative are given below.

3-Alkyl- and 3,3-dialkyldiaziridines and their 1,2-dialkyl derivatives (structures **I**) undergo the acid-induced C–N bond cleavage to form hydrazine derivatives. A method for the synthesis of hydrazine by the hydrolysis of 1,2-unsubstituted diaziridines has preparative advantages over the Raschig synthesis of hydrazine (a two times higher concentration of the final product, the lower energy consumption, the recovery of the starting ketone).[8] The hydrolysis of 1,3-dialkyldiaziridines **1** and 1,3,3-trialkyldiaziridines **2** can afford hydrazones **3** along with hydrazines.

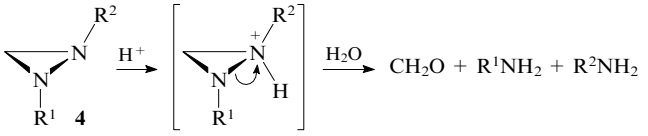


R^1, R^2 = Alk.



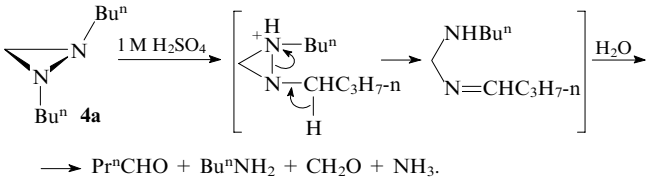
R^1, R^2, R^3 = Alk.

1,2-Dialkyldiaziridines **4** unsubstituted at position 3 undergo the acid-induced N–N bond cleavage to form amines and formaldehyde, from which they were synthesized.

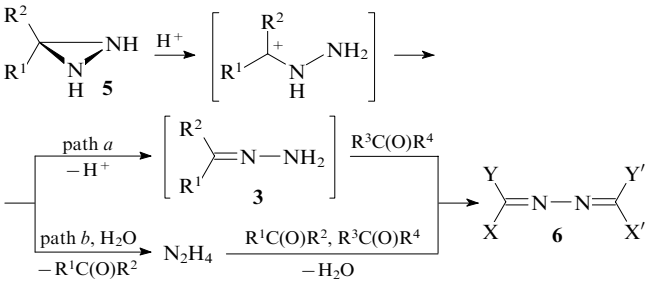


R^1, R^2 = Alk.

In some cases, the reaction proceeds further. For instance, 1,2-di(n-butyl)diaziridine (**4a**) decomposes upon heating with 1 M H_2SO_4 to give butyraldehyde, formaldehyde, n-butylamine and ammonia (the latter two compounds were isolated after alkalinization).[9] The authors proposed the following scheme for this reaction:



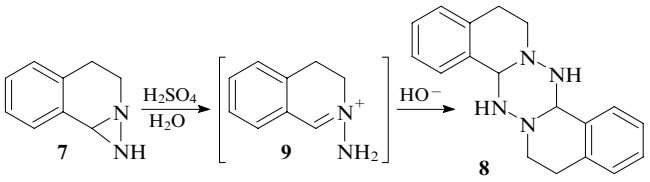
The synthesis of azines **6** performed in the presence of carbonyl compounds is an interesting example of the acid hydrolysis of 3,3-dialkyldiaziridines **5**.[7,10] Apparently, this reaction gives hydrazones **3** or unsubstituted hydrazine as intermediates (in the latter case, a mixture of symmetrical and unsymmetrical azines should be formed).



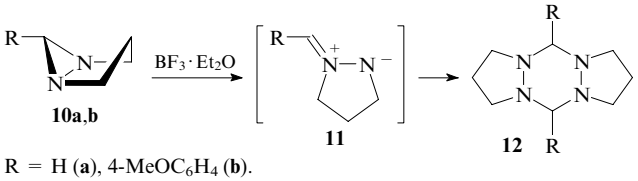
path *a*: X = R^1, Y = R^2, X′ = R^3, Y′ = R^4;
path *b*: X, X′ = R^1, R^3; Y, Y′ = R^2, R^4.

The hydrolysis of tricyclic diaziridine **7** in the presence of sulfuric acid followed by the neutralization with an alkali afforded fused heterocyclic system **8**. Evidently, the formation of this compound proceeds through the acid-induced diaziridine–hydrazone rearrangement giving cationic intermediate **9**. In an alkaline medium, the latter compound

generates an unstable azomethine imine intermediate, which undergoes head-to-tail dimerization.[11,12]

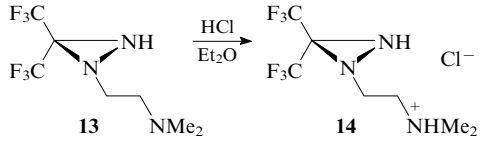


Bicyclic diaziridines of type **IV** have a similar behaviour. For example, the C—N bond cleavage in the diaziridine ring of 1,5-diazabicyclo[3.1.0]hexane (**10a**) and its 6-(4-methoxyphenyl) analogue **10b** occurs in the presence of Lewis acids ($Et_2O \cdot BF_3$, $In(OTf)_3$) to form azomethine imine intermediates **11** followed by their dimerization to give tricyclic structures **12**.[13,14] Unsubstituted bicyclic compound **10a** can be involved in this reaction also in the presence of trace amounts of HCl in dry diethyl ether.[13]

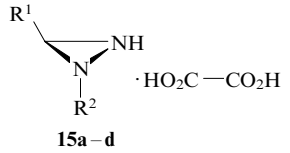


R = H (**a**), 4-$MeOC_6H_4$ (**b**).

Due to the presence of electron-withdrawing substituents CF_3 at the carbon atom of the diaziridine ring, the latter possesses high chemical stability to strong acids. For instance, diaziridine **13** is transformed into stable hydrochloride **14** in the presence of an excess of dry HCl in diethyl ether.[15,16]



In some cases, stable salts of alkyl-substituted diaziridines with acids were isolated; in particular, oxalates **15a–d** were obtained.[17]

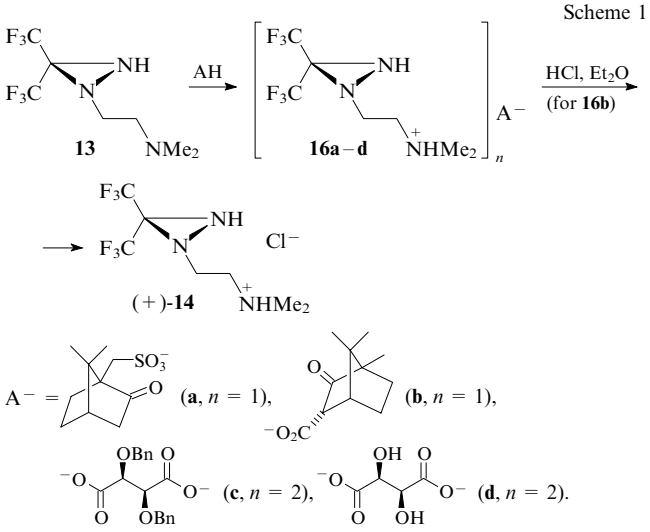


R^1 = Pr^n: R^2 = cyclo-C_6H_{11} (**a**), Bn (**b**); R^1 = n-C_6H_{13}: R^2 = cyclo-C_6H_{11} (**c**), Bu^n (**d**).

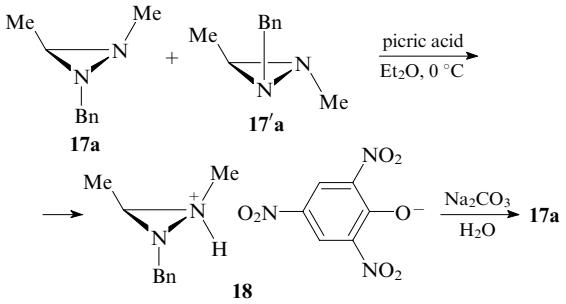
Due to a high nitrogen inversion barrier in monocyclic diaziridines, the latter can be separated into enantiomers, including through the formation of salts with acids. To separate diaziridine **13** into enantiomers, its various diastereometric salts **16** with the following optically active acids were synthesized: L-10-camphorsulfonic (**a**), D-(+)-camphor-3-carboxylic (**b**), (*R*,*R*)-dibenzyltartaric (**c**) and (*R*,*R*)-tartaric (**d**) acids.[15] The anion exchange of salt (+)-**16b** with dry hydrochloric acid in dry diethyl ether gave salt (+)-**14** (Scheme 1).[18]

The reaction of picric acid with a 1:1 mixture of diastereomers of 2-benzyl-1,3-dimethyldiaziridine (**17a** and

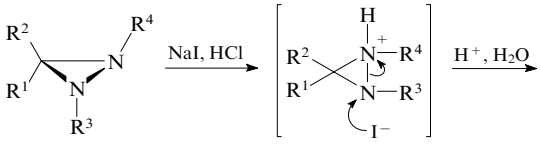
Scheme 1



17′a) followed by fractional crystallization resulted in the formation[19] of 2-benzyl-1,3-dimethyldiaziridinium picrate (**18**) in 65% yield; the reaction of salt **18** with sodium carbonate in water produced diastereomer **17a**. The structure of picrate **18** was confirmed by X-ray diffraction.



The tendency of diaziridines to undergo bond cleavage between the heteroatoms is responsible for their strong oxidizing properties. Diaziridines are among the strongest oxidants in acidic solutions. In this respect, these compounds are comparable with peroxides. In the presence of acids, almost all diaziridines are quantitatively decomposed by iodide anions into carbonyl and amine components. If the diaziridine ring has at least one unsubstituted nitrogen atom, the reaction with iodide proceeds quantitatively in the cold. If both nitrogen atoms are alkylated, the reaction is brought to completion only upon heating. The iodometric titration is used for the determination of the purity of diaziridines and the evaluation of the yield in many studies on the synthesis of diaziridines.[1–7]



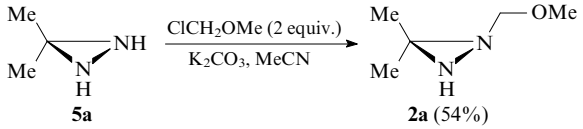
$\longrightarrow R^1C(O)R^2 + R^3NH_3Cl + R^4NH_3Cl + I_2$

R^1, R^2, R^3, R^4 = H, Alk.

III. Alkylation of diaziridines

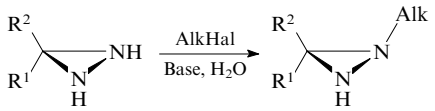
1. N-Alkylation of diaziridines

The possibility of the introduction of an alkyl substituent at the unsubstituted nitrogen atom of the diaziridine ring by the alkylation of *in situ* generated *N*-lithiumdiaziridines by alkyl iodides with the reference on the unpublished data was mentioned for the first time in the review.[3] A single example of the N-monoalkylation of 3,3-dimethyldiaziridine (**5a**) by methoxymethyl chloride was described in the study.[20] It was shown that only the monoalkylation giving 1-methoxymethyl-3,3-dimethyldiaziridine (**2a**) occurs even in the presence of an excess of the alkylating agent.



5a **2a** (54%)

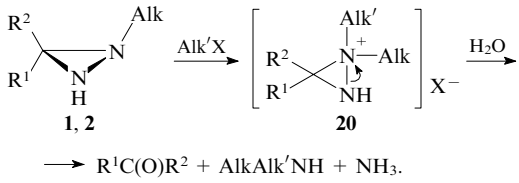
The detailed study of the *N*-alkylation of 3-monoalkyl- (**19**) and 3,3-dialkyldiaziridines **5** and the use of this reaction for preparative purposes were described in the publication.[21] It was found that diaziridines **19** and **5** are rather easily subjected to alkylation at one of the nitrogen atoms by alkyl halides and dimethyl sulfate in the presence of bases to form N-monoalkyl-substituted diaziridines **1** and **2**, respectively, in satisfactory yields.



5a,**b**; **19a** **1**, **2** (48% – 50%)

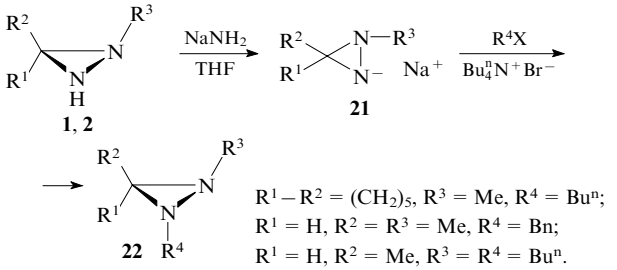
$R^1 = R^2 =$ Me (**5a**), $R^1 - R^2 = (CH_2)_5$ (**5b**); $R^1 =$ H, $R^2 =$ Me (**19a**); Alk = Pr^n, Pr^i, Bu^n, $CH_2{=}CHCH_2$, $HC{\equiv}CCH_2$, Bn, $MeN(NO_2)CH_2$; Hal = Br, Cl; Base = KOH, $NaHCO_3$, Et_3N.

Alkyl bromides proved to be the most efficient alkylating agents among alkyl halides. Thus, the use of chlorides resulted in lower yields, and alkyl iodides caused the partial decomposition of diaziridines. An increase in the amount of the alkylating agent did not lead to the formation of 1,2-dialkyl-substituted diaziridines. This fact, along with insufficiently high yields of *N*-monoalkyldiaziridines **1** and **2**, as well as the formation of carbonyl compounds as by-products used for the synthesis of the starting diaziridines, suggests that the second molecule of the alkylating agent attacks the more basic (alkylated) nitrogen atom in the resulting *N*-monoalkyldiaziridines (like the alkylation of hydrazine) to give cation **20**, which is subjected to the ring opening and is transformed into the carbonyl compound, secondary amine and ammonia in the reaction with water.



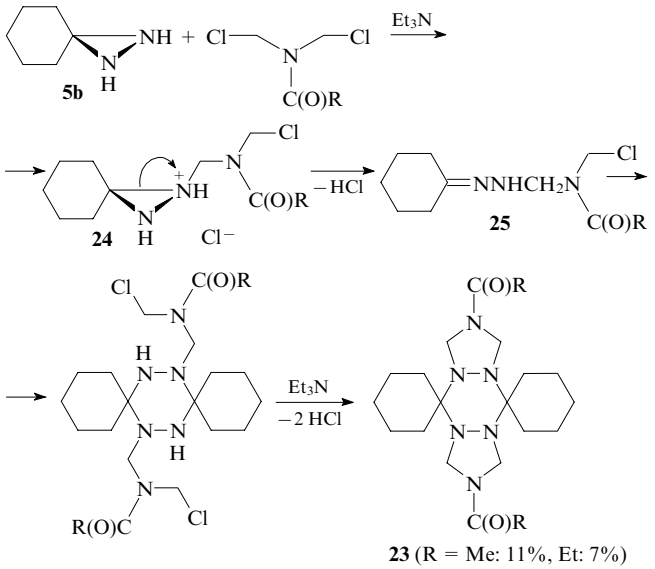
1, **2** **20**

The introduction of an alkyl substituent at the second nitrogen atom was made possible[21] only through the metallation of *N*-monoalkyldiaziridines by sodium amide in THF to form sodium salts **21** followed by their alkylation to 1,2-dialkyldiaziridines **22**. The rate of alkylation of salts **21** increases in the presence of tetraalkylammonium salts in the reaction mixture, due to which the reaction can be performed in diethyl ether or even in hexane.



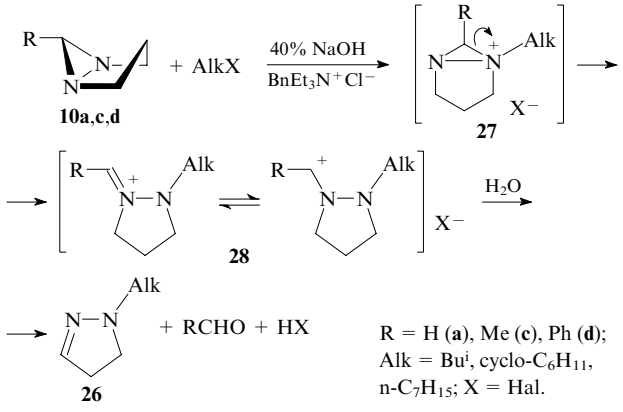
1, **2** **21** **22**

The unusual example of the alkylation is the reaction of 3,3-pentamethylenediaziridine (**5b**) with *N*,*N*-bis(chloromethyl)carboxamides to form spiro compounds **23** in low yield.[22] The authors suggested that this reaction proceeds *via* the monoalkylation of diaziridine **5b** to form intermediates **24** followed by the opening of the three-membered ring to give hydrazones **25**. The dimerization of the latter followed by the intramolecular alkylation affords pentacyclic systems **23**.



23 (R = Me: 11%, Et: 7%)

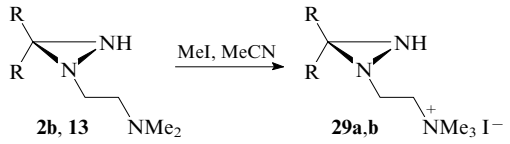
The alkylation of bicyclic diaziridines at the nitrogen atoms of the diaziridine ring was investigated in only one study. Thus, the reaction of 1,5-diazabicyclo[3.1.0]hexanes **10** with alkyl halides in the presence of phase transfer



catalysts produces 1-alkyl-2-pyrazolines **26**.[23] The reaction mechanism was described as the attack of the alkylating agent on one of the nitrogen atoms of bicyclic system **10** to form salts **27**. The subsequent C—N bond cleavage in the diaziridine ring of salts **27** gives new intermediates **28**, which are analogues of α-haloalkylamines, whose stabilization through hydrolytic cleavage finally leads to pyrazolines **26**.

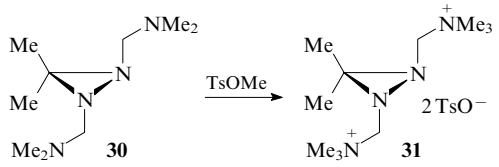
2. Alkylation of diaziridines at the side chain

It is possible to perform alkylation of diaziridines without the involvement of the nitrogen atoms of the ring if the compound contains a stronger nucleophilic centre, for example, the amino group, in the side chain. For example, the reaction of 1-(2-dimethylaminoethyl)-3,3-dimethyldiaziridine (**2b**) with methyl iodide affords stable crystalline quaternary salt **29a**.[24] 1-(2-Dimethylaminoethyl)-3,3-bis(trifluoromethyl)diaziridine (**13**) behaves in a similar way and gives salt **29b**.[12]



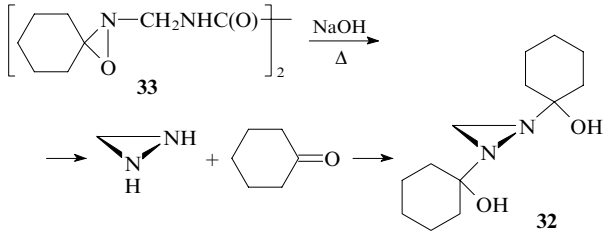
R = Me (**2b**, **29a**), CF_3 (**13**, **29b**).

Bis-quaternary salt **31** was synthesized by the reaction of 1,2-bis(dimethylaminomethyl)-3,3-dimethyldiaziridine **30** with methyl tosylate.[25]

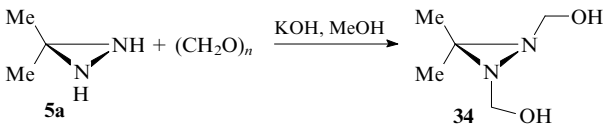


IV. Reactions of 1- and 1,2-unsubstituted diaziridines with carbonyl compounds

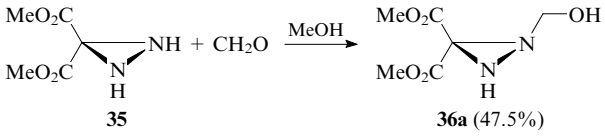
The NH groups of nitrogen-unsubstituted diaziridines readily react with carbonyl compounds to form α-hydroxyalkyl derivatives. Thus, the simplest unsubstituted diaziridine forms adduct **32** with two cyclohexanone molecules. This adduct is isolated in the case of the *in situ* generation of diaziridine from bisoxaziridine **33** in its reaction with alkali upon heating.[7]



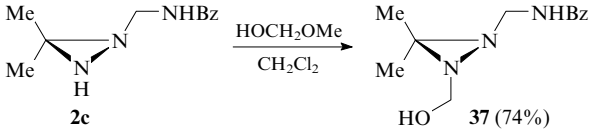
3,3-Dimethyldiaziridine (**5a**) adds two formaldehyde molecules to form crystalline 1,2-bis(hydroxymethyl)-3,3-dimethyldiaziridine **34**. The same product was synthesized by the reaction of α-polyoxymethylene depolymerized in methanol with 3,3-dimethyldiaziridine (**5a**) in the presence of a catalytic amount of potassium hydroxide.[26]



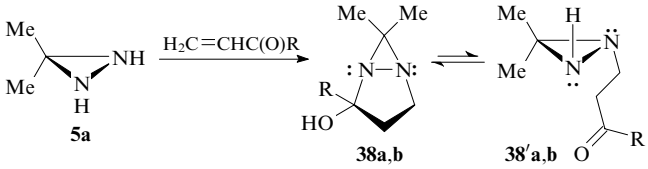
The reaction of dimethyl diaziridine-3,3-dicarboxylate (**35**) with formaldehyde under reflux in methanol for 1 h produces monoadduct **36a**.[27]



The reactions with carbonyl compounds, unlike the alkylation, can proceed at the free NH group of N-monosubstituted diaziridines. For instance, the reaction of diaziridine **2c** with methoxymethanol in dichloromethane produces hydroxymethyl derivative **37**.[28]

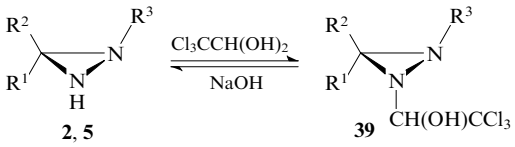


An interesting example of the condensation of the NH group of diaziridines with the carbonyl group is provided by the intramolecular reaction observed for bicyclic diaziridines **38a**,**b**, which were synthesized by the reaction of vinylcarbonyl compounds with 3,3-dimethyldiaziridine (**5a**). In this case, bicyclic diaziridines **38a**,**b** with *cis*-oriented LP exist in an equilibrium mixture with the open form **38′a**,**b** with *trans*-oriented LP.[29]



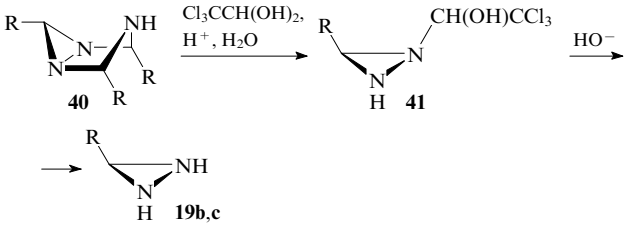
R = H (**a**), Me (**b**).

The reaction of chloral with diaziridines containing at least one unsubstituted nitrogen atom produces well-crystallizable addition products **39**. If both nitrogen atoms are unsubstituted, only one chloral molecule is added. Adducts **39** are suitable both for the characterization of diaziridines and the isolation of the latter from mixtures. The starting diaziridines are regenerated from chloral hydrate derivatives **39** after the treatment with alkali.[7,9]



R^1, R^3 = Alk, R^2 = H, Alk.

The mild acidic cleavage of 2,4,6-trialkyl-l,3,5-triazabicyclo[3.1.0]hexanes **40** at the triazolidine ring in the presence of chloral hydrate affords derivatives **41**. The alkaline hydrolysis of the latter produced first representatives of 3-monoalkyldiaziridines **19b**,**c** in low yields.[7,30]

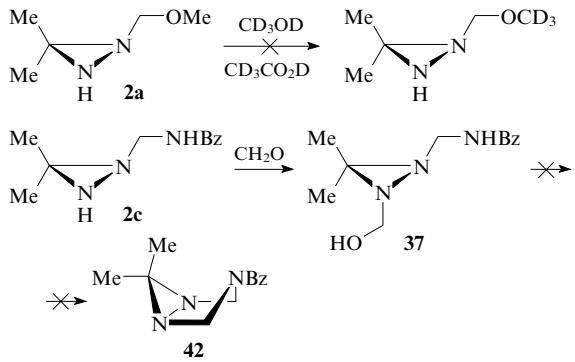


R = Pr^n (**b**), Bu^t (**c**).

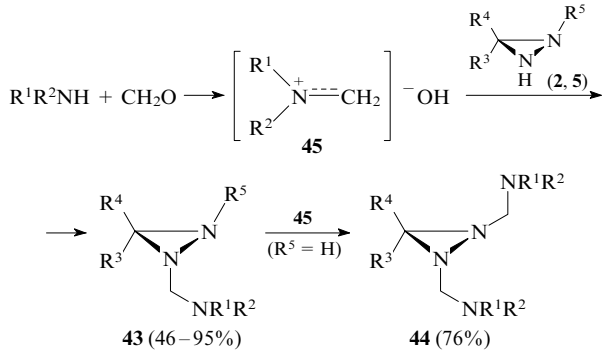
V. Mannich reaction involving diaziridines

1. N-Aminoalkylation of diaziridines

The α-aminoalkylation of diaziridines follows the mechanism of the Mannich reaction, in which these compounds act exclusively as NH-acids. It was shown that diaziridines with one or both unsubstituted nitrogen atoms do not form diaziridinomethyl derivatives with each other, as well as with aziridines in the reactions with formaldehyde.[31] In addition, the fact that the α-aminomethylation by diaziridines is forbidden was shown in the study of the behaviour of 1-methoxymethyl-3,3-dimethyldiaziridine (**2a**) (the absence of the methoxy exchange with deuteriomethanol in the presence of CD_3CO_2D) [20] and in the study, where it was shown that the cyclization of hydroxymethyldiaziridine **37** to bicyclic system **42** cannot be performed.[28]

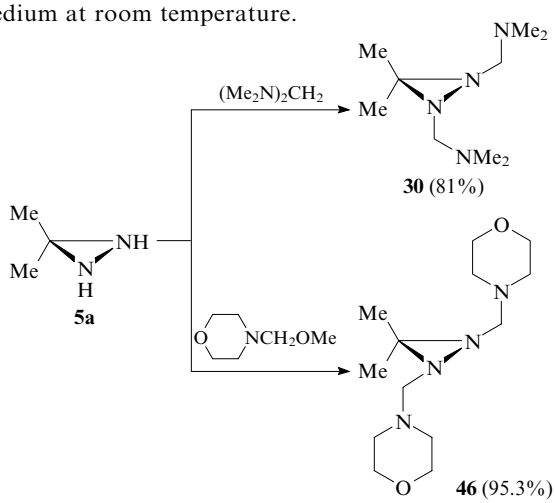


From these results it is evident that the formation of *N*-aminomethyldiaziridines **43** or **44** by the reactions of 1- or 1,2-unsubstituted diaziridines **2** and **5** with amines and formaldehyde (α-aminomethylation) proceeds *via* electrophilic attack of carbenium iminium cation **45**, which is generated from formaldehyde and amine that is more basic than diaziridines, on the nitrogen atom of the diaziridine ring.

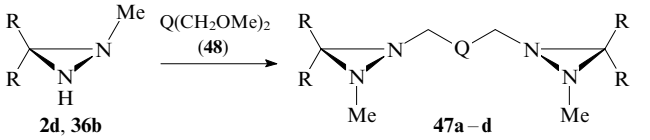


R^1, R^2, R^3, R^4 = Alk; R^5 = H, Alk.

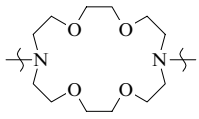
The drawback of this method for the synthesis of α-aminomethyldiaziridines is that it is accompanied by the side reaction giving methylenebis(amines). To prevent the latter reaction, alkylenebis(amines), alkoxymethyl- and bis(alkoxymethyl)amines are used as aminomethylating agents.[16,25] In the study,[25] 1,2-bis(aminomethyl)diaziridines **30** and **46** were synthesized by the reaction of 3,3-dimethyldiaziridine (**5a**) with methylenebis(dimethylamine) and *N*-methoxymethylmorpholine, respectively, in an aqueous medium at room temperature.



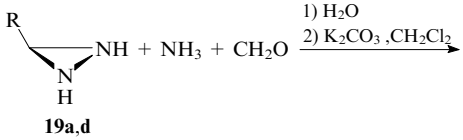
This approach was used [16,25] to synthesize a series of bis(diaziridines) **47a–d** by the reactions of 1,3,3-trisubstituted diaziridines **2d** and **36b** with various bis(methoxymethyl)amines **48**. Compounds **47** were studied to reveal psychotropic activity.

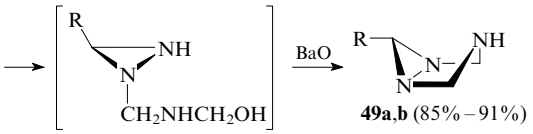


R = Me (**2d**), CO_2Me (**36b**);

Compound **47**	R	Q	Yield (%)
a	CO_2Me	NBu^t	91
b	Me	NBu^t	81
c	CO_2Me	NBu^t	83
d	Me		95

The reactions of 1,2-unsubstituted diaziridines with carbonyl compounds and primary aliphatic amines or ammonia produced 1,3,5-triazabicyclo[3.1.0]hexanes as bicyclic products of the Mannich reaction. For example, the condensation of 3-monoalkyldiaziridines **19a**,**d** with ammonia and formaldehyde in water followed by the fast transfer of the reaction mixture into an organic solvent (dichloromethane) and the use of dehydrating agents

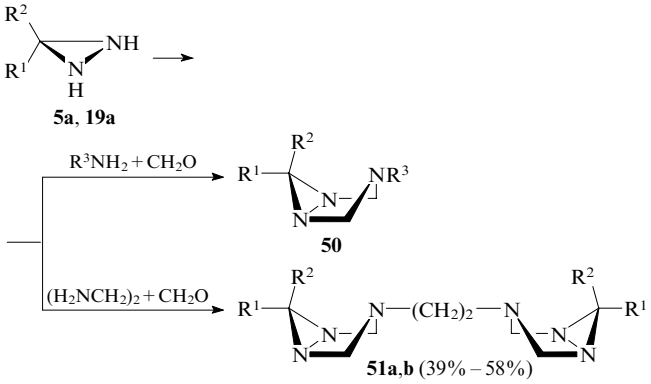




R = Me (**19a**, **49a**), Et (**19d**, **49b**).

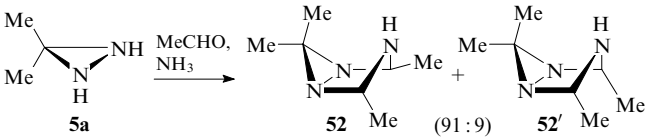
(potassium carbonate or barium oxide) afforded the first representatives of 2,3,4-unsubstituted 1,3,5-triazabicyclo[3.1.0]hexanes **49a**,**b**.[28, 32] The transfer of the reaction mixture into an organic solvent and the use of strong dehydrating agents are necessary to prevent the thermodynamically controlled formation of urotropine.

3,3-Dialkyldiaziridines **5** do not form bicyclic compounds **49** under these conditions. However, the reactions of compounds **5** with primary aliphatic amines and formaldehyde in chlorine-containing organic solvents in the presence of potassium carbonate gave the corresponding 2,4-unsubstituted 3,6,6-trialkyl-1,3,5-triazabicyclo[3.1.0]-hexanes **50**,[28, 32] whereas the reactions with the use of ethylenediamine produced bis(bicyclic) systems **51**.[28] Under similar conditions, 3,6-dialkyl-substituted bicyclic structures **50** and **51** are generated from 3-monoalkyldiaziridines **19**.

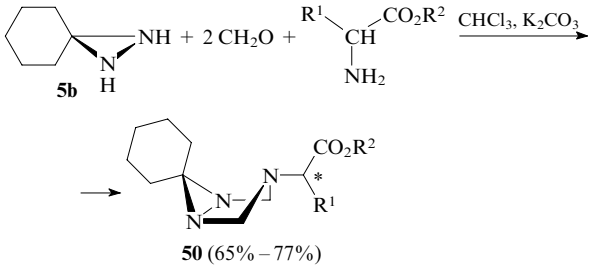


5a, **51a**: $R^1 = R^2 = Me$; **19a**, **51b**: $R^1 = H$, $R^2 = Me$;
50: $R^1 = R^2 = Me$: $R^3 = Me$, $(CH_2)_2OH$, CH_2NHBz, $CH_2CH(OMe)_2$;
$R^1 = H$, $R^2 = Me$: $R^3 = Me$, Et.

The α-aminomethylation of 3,3-dimethyldiaziridine (**5a**) giving 1,3,5-triazabicyclo[3.1.0]hexane derivatives can be performed with the use of other aldehydes, for example, with acetaldehyde, resulting in the formation of compound **52**.[33] In this study, the stereochemical features of the formation of compound **52** were analyzed. It was found that racemate **52** is the major product in the mixture of diastereomers **52** and **52′**.



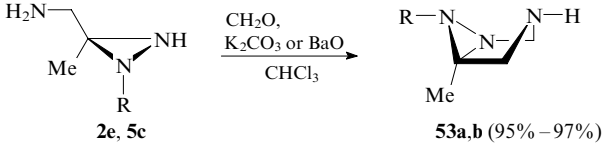
Using 3,3-pentamethylenediaziridine (**5b**) as an example, it was shown that the α-aminomethylation can be performed with α-amino acids and their derivatives; these reactions produce the corresponding 3-substituted 1,3,5-triazabicyclo[3.1.0]hexanes **50**, including enantiomerically pure compounds.[34]



$R^1 = R^2 = H$ (as a potassium salt); $R^1 = H$, $R^2 = Et$;
$R^1 = Pr^i$, $R^2 = Me$ (*R* and *S* enantiomers).

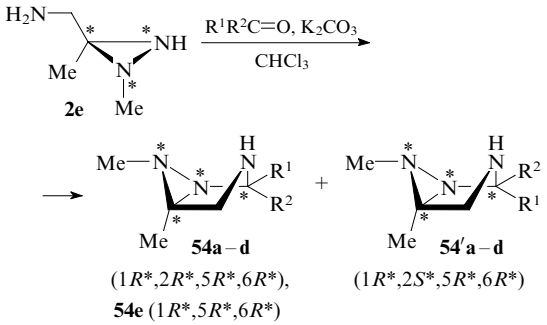
2. Synthesis of 1,3,6-triazabicyclo[3.1.0]hexanes

The intramolecular α-aminomethylation of 3-(aminomethyl)diaziridines underlay the synthesis of 1,3,6-triazabicyclo[3.1.0]hexanes. For example, first representatives of 1,3,6-triazabicyclo[3.1.0]hexanes **53a**,**b** were synthesized by the reactions of 3-aminomethyl-3-methyl- (**5c**) and 3-aminomethyl-1,3-dimethyldiaziridines (**2e**) with formaldehyde in $CHCl_3$ with the use of potassium carbonate or barium oxide as the dehydrating agent.[32]

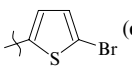


R = H (**5c**, **53a**), Me (**2e**, **53b**).

The reactions of 3-aminomethyldiaziridine **2e** with various aldehydes and ketones as carbonyl compounds produced 2,5,6-trisubstituted 1,3,6-triazabicyclo[3.1.0]hexanes **54**. It was shown that the reactions with aromatic and heteroaromatic aldehydes are diastereoselective and give two diastereomers, 1*R**,2*R**,5*R**,6*R** (**54a** – **d**) and 1*R**,2*S**,5*R**,6*R** (**54′a** – **d**), of 2-aryl(hetaryl)-1,3,6-triazabicyclo[3.1.0]hexanes in a ratio of 3 : 20, with diastereomers **54′a** – **d** prevailing, in a total yield of 45% – 78%.[35] The major diastereomers were isolated in all cases. The X-ray diffraction study showed that diastereomer **54′d** crystallizes as a conglomerate. The reaction with symmetrical ketones ($R^1 = R^2 = Me$) affords exclusively racemate (1*R**,5*R**,6*R**)-**54e**.



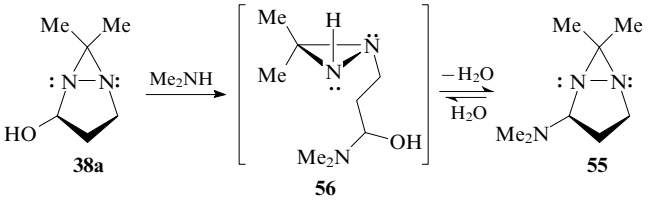
$R^1 = H$: R^2 = 2-HOC_6H_4 (**a**), 4-$MeOC_6H_4$ (**b**), 2,6-$(HO)_2C_6H_3$ (**c**),



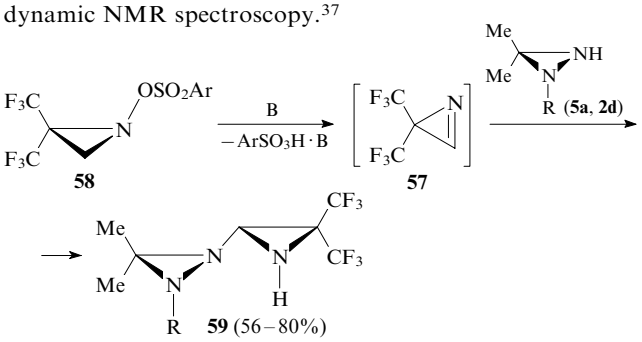
(**d**); $R^1 = R^2 = Me$ (**e**).

3. Other α-aminoalkylation reactions of N-unsubstituted diaziridines

Only one example of the synthesis of 1,5-diazabicyclo[3.1.0]hexanes by the intramolecular α-aminoalkylation of bicyclic diazridine **38a** with dimethylamine was reported. The reaction produced 2-dimethylamino derivative **55**, which exists in solution in the bicyclic *cis* form (^{1}H NMR spectroscopic data in $CDCl_3$ and CD_3OD). Evidently, the reaction proceeds through the formation of the open *trans* form **56**.[36]



3,3-Bis(trifluoromethyl)azirine-1 (**57**), which is generated by the reaction of 1-arylsulfonyloxy-2,2-bis(trifluoromethyl)aziridines **58** with bases, reacts with diaziridines **5a** and **2d** to form adducts **59**. For these derivatives, all theoretically possible stereoisomers were detected by dynamic NMR spectroscopy.[37]



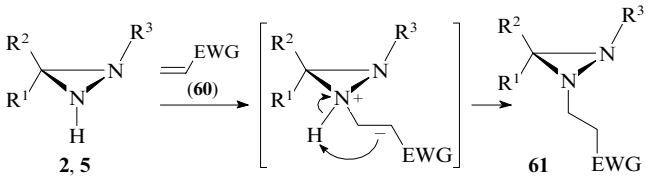
Ar = Ph, 4-MeC_6H_4; R = H (**5a**), Me (**2d**); B is a base.

VI. Reactions of diaziridines with activated unsaturated compounds

1. Reactions of monocyclic diaziridines with activated alkenes

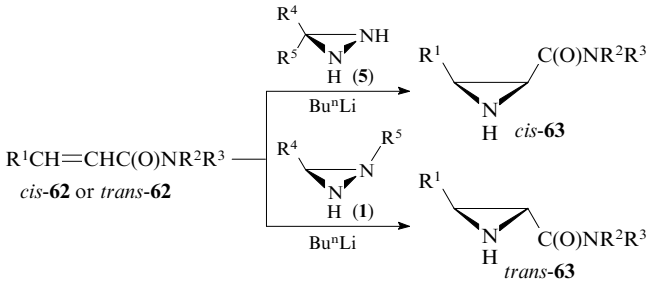
Reactions of activated alkenes **60** (EWG is the activating group) with monocyclic diaziridines were described only for 1- and 1,2-unsubstituted diaziridines, which can form

Scheme 2



$R^1 = R^2 = Me$, $R^1 - R^2 = (CH_2)_5$, $R^1 = Me$, $R^2 = Et$;
R^3 = H, Me, $(CH_2)_2OH$, $(CH_2)_2Ac$, $(CH_2)_2CN$, CH_2Ph;
EWG = SO_2Ar, C(O)Me, CHO.

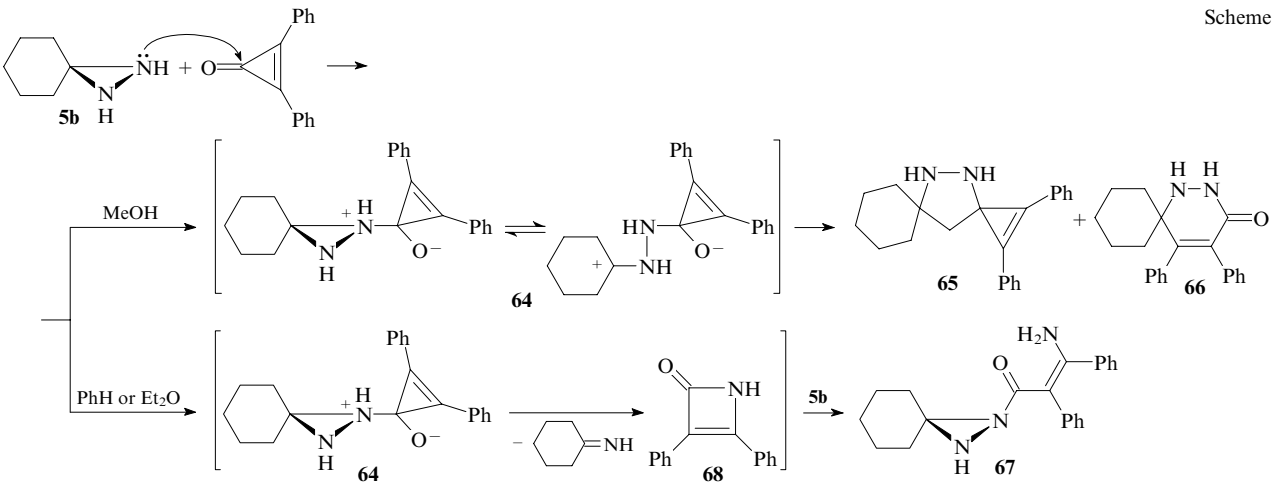
Scheme 3



Michael adducts **61**, like secondary amines, with either retention of the diaziridine ring (Scheme 2)[7, 36, 38–41] or its cleavage (Scheme 3 and 4).[42–46] Products of the diaziridine–hydrazone rearrangement typical of such intermediates were detected in none of the cases.

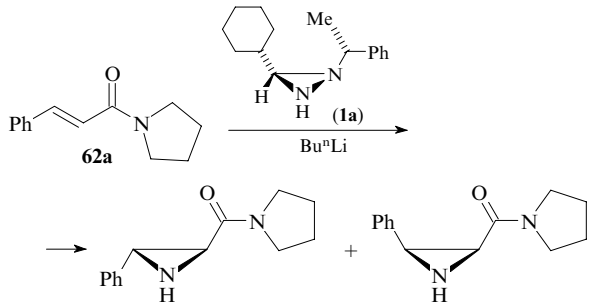
The authors of the studies[42–44] discovered the highly diastereo- and enantioselective aziridination of α,β-unsaturated amides **62** by 3,3- and 1,3-dialkyldiaziridines **5** and **1**, respectively. The reaction proceeds in THF in the presence of Bu^nLi at −30 °C. It was found that the use of 3,3-dialkyldiaziridines **5** in this reaction leads to the formation of *cis*-aziridinecarboxamides *cis*-**63**, whereas the reactions with 1,3-disubstituted diaziridines **1** result in the *trans*-selective aziridination to form *trans*-aziridines *trans*-**63** regardless of the geometry of the starting unsaturated amide **62** (see Scheme 3). The stereoselectivity of aziridination is attributed to different conformations of intermediate enolates. Before these studies, the aziridination has been known only for oxaziridines.[1, 7] To examine the possibility of the enantioselective aziridination, several optically active diaziridines were synthesized. It was shown that, as in the case of racemic diaziridines, the *cis*- and *trans*-aziridination path-

Scheme 4



ways remain the same depending on the structure of the starting diaziridines, but high enantioselectivity of the process is observed in the reactions with the use of optically active diaziridines.

For example, the reaction of amide **62a** with chiral diaziridine **1a** in the presence of Bu^nLi produces a mixture of *trans*- and *cis*-aziridines **63a** with high enantioselectivity, with isomer *trans*-**63a** prevailing.



trans-**63a** (76%, 98% *ee*) *cis*-**63a** (3%, *ee* >99%)

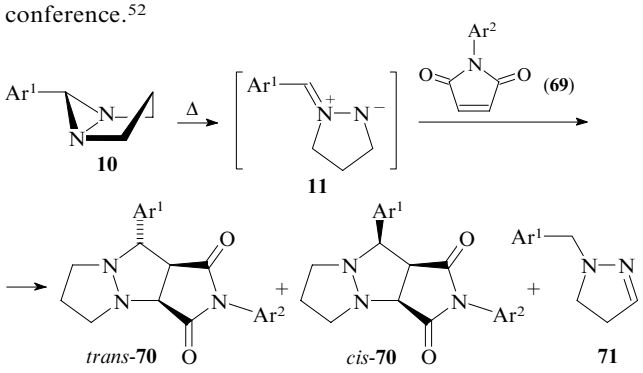
The reaction of 3,3-pentamethylenediaziridine (**5b**) with diphenylcyclopropenone in methanol proceeds through the formation of zwitterionic intermediate **64**, which is stabilized as two isomeric adducts **65** and **66** (see Scheme 4).[45] In aprotic media (in benzene or diethyl ether), the reaction with two equivalents of diaziridine **5b** gives adduct **67**. Apparently, the reaction proceeds through the formation of intermediates **64** and **68**. As can be seen from the structures of the reaction products, the nitrogen lone pair of the diaziridine ring attacks the carbonyl carbon atom rather than the alkene carbon atom of diphenylcyclopropenone regardless of the nature of the solvent.[46]

2. Reactions of bicyclic diaziridines with activated alkenes

These reactions were studied in most detail for 1,5-diazabicyclo[3.1.0]hexanes **10**. The latter compounds do not directly react with activated alkenes; however, after the cleavage of the C–N bond in the diaziridine ring and the formation of azomethine imine intermediate **11**, these compounds form the corresponding bicyclic cycloaddition products. Azomethine imines **11** can be generated either thermally or in the presence of Lewis acids [$BF_3 \cdot Et_2O$, $In(OTf)_3$] under milder conditions.

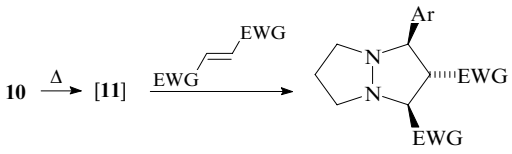
a. Thermal generation of azomethine imines from 6-aryl-1,5-diazabicyclo[3.1.0]hexanes

The reactions of thermally generated azomethine imines **11** with activated alkenes were studied in detail in the Saint Petersburg State University by the research team headed by Kostikov, Molchanov and Koptelov.[47–51] They showed that the thermolysis of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** at 110–140 °C (refluxing in toluene or xylene) in the presence of various dipolarophiles, including activated alkenes (*N*-arylmaleimides, dialkyl fumarates, dicyanoethylene, diphenylcyclopropenone) affords bicyclic nitrogen-containing adducts of the [3+2]-dipolar cycloaddition to the generated azomethine imine intermediate **11**. In particular, tricyclic heterocyclic systems **70** were synthesized by heating 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** in the presence of *N*-arylmaleimides **69**. The reaction is stereoselective and gives *trans* isomers as the major products. The total yield of the *trans* and *cis* isomers of **70** is 60%–85%. The selectivity of the reaction decreases in the presence of electron-withdrawing substituents in the aromatic moieties Ar^1. The thermolysis of compounds **10** in the absence of dipolarophiles affords pyrazolines **71** that are formed due to stabilization of azomethine imines **11** *via* a [1,4-H]-shift. Pyrazolines **71** are formed in small amounts also by the thermolysis of compounds **10** in the presence of *N*-arylmaleimides **69**. The fraction of the *trans* isomers substantially increases in the presence of *ortho* substituents in the aromatic moiety Ar^2 of *N*-arylmaleimides **69**.[49] Similar cycloaddition products were obtained by the same research team in the studies of the thermal cleavage of 7-aryl-1,6-diazabicyclo[4.1.0]heptanes in the presence of *N*-arylmaleimides; however, these results were presented only as a poster at the conference.[52]



Ar^1 = Ph, 4-$MeOC_6H_4$, 4-MeC_6H_4, 4-ClC_6H_4;
Ar^2 = 2-ClC_6H_4, 2-BrC_6H_4, 2,4-$Me_2C_6H_3$, 2,5-$Me_2C_6H_3$, 1-Naph, *etc.*

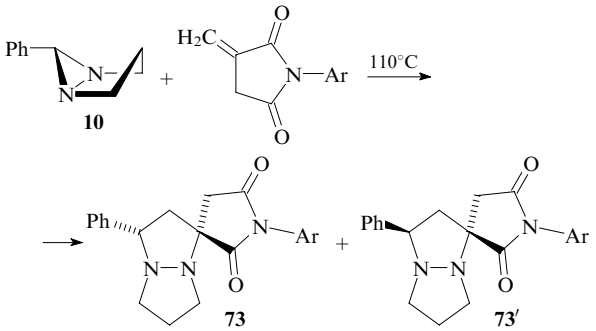
The thermolysis of diazabicyclohexanes **10** in the presence of fumaric acid derivatives affords 1,3-dipolar cycloaddition products **72**, in which protons and substituents in the pyrazolidine ring are *trans*,*trans*-oriented.[49]



72 (up to 74%)

Ar = 4-XC_6H_4 (X = H, MeO, Cl, Br, Me, CN);
EWG = CN, CO_2Ph, CO_2Me.

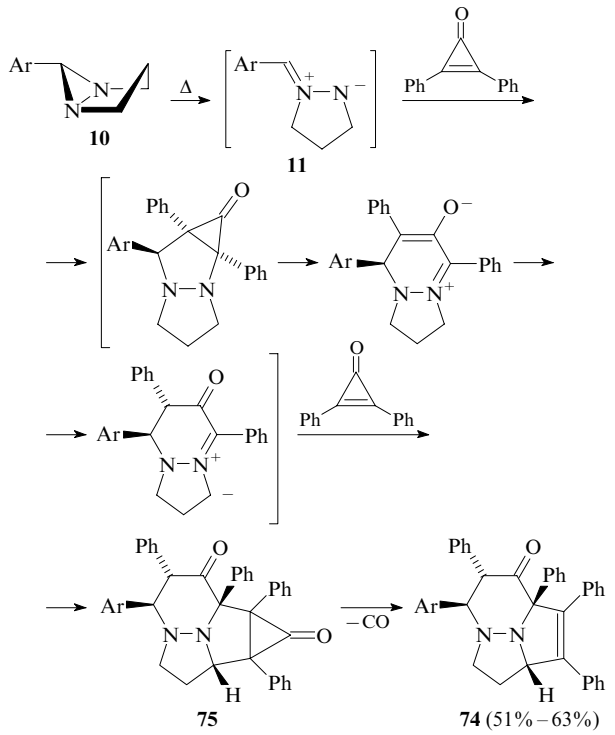
The generation of azomethine imine **11** by the thermolysis of bicyclic compounds **10** in the presence of activated alkenes containing the unsymmetrically substituted double bond (*N*-arylimides of 2-aryl-substituted maleic, citraconic and itaconic acids) also results in the formation of the corresponding 1,3-dipolar cycloaddition products. These reactions are highly regioselective.[51] For example, the reaction with *N*-arylimides of itaconic acid produces spiro-



Ar = Ph, 4-ClC_6H_4.

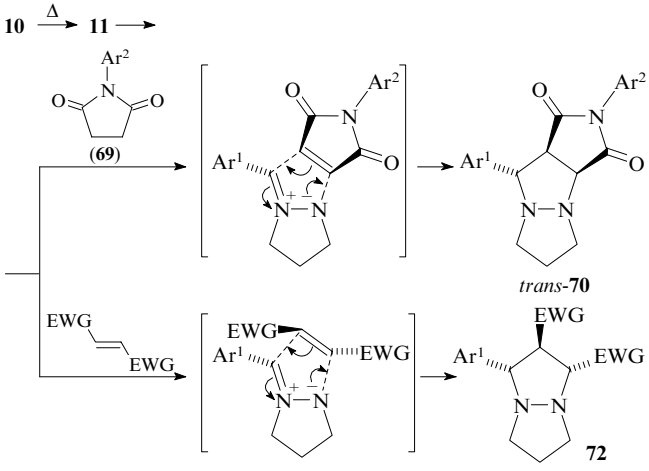
fused tricyclic systems **73** as mixtures of diastereomers (**73** and **73′**) in a ratio of 3 : 2 and a total yield of up to 65%.

The reaction with diphenylcyclopropenone is an interesting example of transformations of azomethine imines **11**.[50] This transformation involves the sequential addition of two molecules of the dipolarophile to form tricyclic products **74** with high stereoselectivity and in good yields. It should be noted that only the C=C double bond of the starting diphenylcyclopropenone is involved in both cycloaddition reactions, the carbonyl group being eliminated as CO from the primary cycloaddition product **75** in the second reaction.



Ar = Ph, 4-MeOC$_6$H$_4$, 4-BrC$_6$H$_4$, 4-ClC$_6$H$_4$.

The regio- and stereoselectivity of the reaction was investigated in detail[47–51] for the reactions of azomethine imines **11** generated by the thermolysis of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** with *N*-arylmaleimides **69** and *trans*- and *cis*-disubstituted activated alkenes. The fact that the reactions with *N*-arylmaleimides **69** and *trans*-disubstituted alkenes (fumaric acid derivatives) give adducts

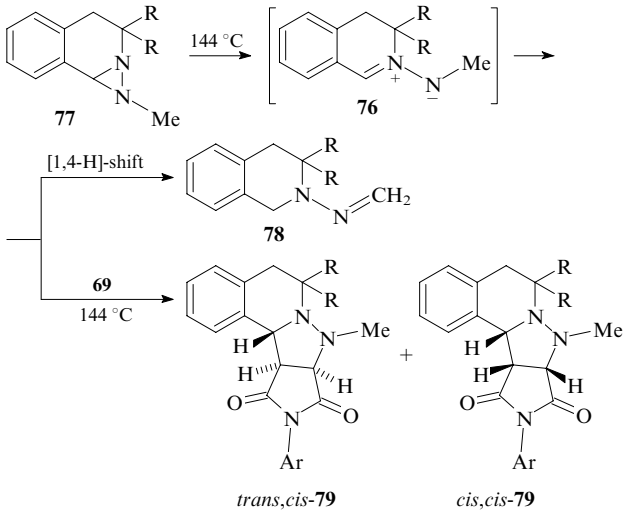


EWG = CN, CO_2Me, CO_2Ph.

trans-**70** with *trans*,*cis*-oriented protons in the newly formed pyrazolidine ring and compounds **72** with *trans*,*trans*-oriented protons, respectively, as the major products, was attributed to the *exo*- or *endo*-approach of the dipolarophile to azomethine imine **11**, which minimizes the steric interaction between the aryl substituent of azomethine imine and the substituent of the activated alkene.

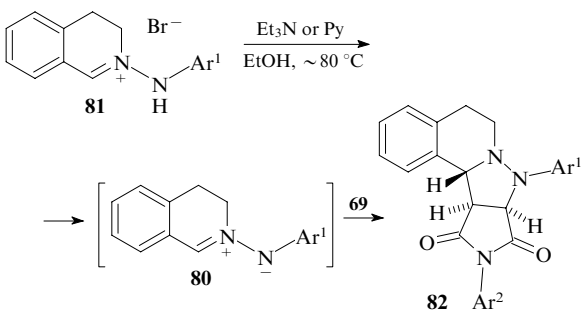
b. Thermal generation of azomethine imines containing the exocyclic nitrogen atom from fused diaziridine derivatives

Azomethine imines **76** containing the exocyclic nitrogen atom can be generated *in situ* in *o*-xylene at 144 °C *via* C–N bond cleavage in the diaziridine ring annulated to dihydroisoquinoline (compound **77**). In the reaction conditions, azomethine imines **76** undergo a [1,4-H]-shift to form imines **78** or, in the presence of *N*-arylmaleimides **69**, give two isomeric adducts, *trans*,*cis*-**79** and *cis*,*cis*-**79**, with the former prevailing (from 3 : 1 to 8 : 1), which is attributed to the *exo*-approach of the dipolarophile to the 1,3-dipole of azomethine imine **76**.[53, 54]



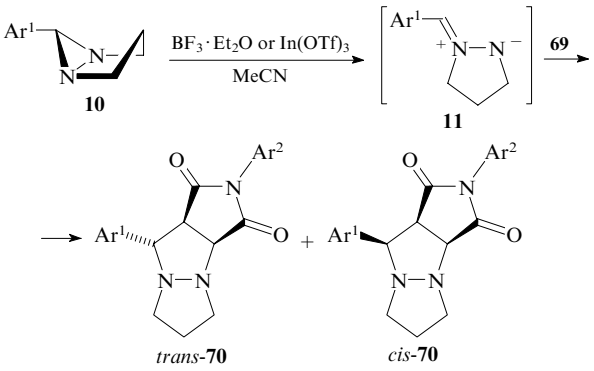
R = H, Me; Ar = 4-BrC$_6$H$_4$, 4-MeOC$_6$H$_4$, 2,6-Cl$_2$C$_6$H$_3$, 2,6-Me$_2$C$_6$H$_3$, Mes, 1-Naph.

These authors also performed the *in situ* synthesis of azomethine imines **80** related to azomethine imines **76** by the catalytic dehydrobromination of 2-arylamino-3,4-dihydroisoquinolinium bromides **81** in the presence of triethylamine or pyridine in ethanol at 80 °C followed by the addition of *N*-arylmaleimides **69** to the reaction mixture to form the *trans*,*cis*-adduct of 1,3-dipolar cycloaddition **82**. This result was accounted for by the *exo*-approach of the dipolarophile to the 1,3-dipole of the *E* form of azomethine imines **80**.[55]



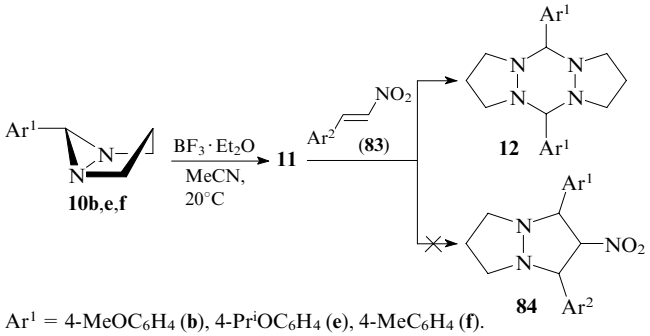
c. Catalytic generation of azomethine imines from 6-aryl-1,5-diazabicyclo[3.1.0]hexanes

Another approach to the generation of azomethine imines **11** from 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** is based on the catalytic cleavage of the diaziridine ring at the C–N bond. This approach was proposed also by the research group headed by Kostikov[14] based on the reaction of azomethine imines **11** generated in the presence of Lewis acids [$BF_3 \cdot Et_2O$ or $In(OTf)_3$] with *N*-arylmaleimides **69** to form cycloaddition products **70**. It was shown that in this case, the reaction proceeds as the above-described thermolytic reaction but affords the *cis* isomer *cis*-**70** as the major product.



Ar^1 = Ph, 4-XC_6H_4 (X = Me, MeO, Cl), 3-$O_2NC_6H_4$;
Ar^2 = Ph, 4-YC_6H_4 (Y = Me, MeO, Br, NO_2).

The further study of the 1,3-dipolar cycloaddition of activated unsaturated compounds to azomethine imines **11** generated *via* the catalytic cleavage of the diaziridine ring in 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** in the presence of $BF_3 \cdot Et_2O$ was performed in the N D Zelinsky Institute of Organic Chemistry of the Russian Academy of Sciences.[56, 57] By analogy with the above-considered cycloaddition reactions of activated alkenes with azomethine imines **11**, it would be expected that the reaction of β-nitrostyrenes **83** with these intermediates would proceed *via* the Michael addition to form 1,3-diaryl-2-nitrotetrahydro-1*H*,5*H*-pyrazolo[1,2-*a*]pyrazoles **84**. However, the reaction in acetonitrile produced only hexahydrotetrazine derivatives **12**, dimers of azomethine imines **11**.

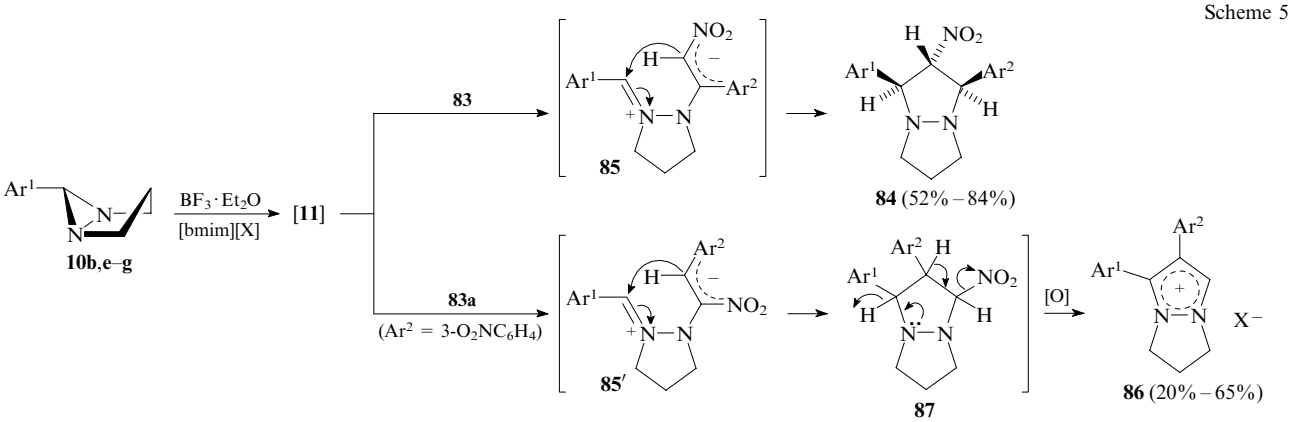


Ar^1 = 4-$MeOC_6H_4$ (**b**), 4-$Pr^iOC_6H_4$ (**e**), 4-MeC_6H_4 (**f**).

The reaction was made possible only by using ionic liquids (IL), such as 1-butyl-3-methylimidazolium tetrafluoroborate or hexafluorophosphate {[bmim][BF_4]([PF_6])}, which are stable in air and resistant to atmospheric moisture (Scheme 5). Ionic liquids are currently widely used as an environmentally attractive alternative to conventional organic solvents,[58–62] in particular, in the 1,3-dipolar cycloaddition reactions.[63, 64] Ionic liquids have considerable advantages over conventional solvents: they are nonflammable and nonvolatile and can be easily regenerated and repeatedly used without a decrease in the yield of the final product. Moreover, many reactions proceed faster in IL. Various organic reactions performed in IL belong to a promising field of organic chemistry, so-called green chemistry.

At room temperature or under slight heating, the $Et_2O \cdot BF_3$-catalyzed reaction produced the target compounds **84**. The reaction of β-nitrostyrenes **83** with azomethine imine **11** follows the mechanism of the Michael addition and proceeds, apparently, through zwitterionic intermediate **85**. However, in addition to compounds **84**, pyrazolo[1,2-*a*]pyrazolium tetrafluoroborates and hexafluorophosphate **86** were unexpectedly isolated in the reaction of the starting bicyclic compounds **10e**,**f**,**g** with β-nitrostyrene (**83a**). The formation of these compounds can be represented as the result of the anti-Michael addition of β-nitrostyrene (**83a**) to azomethine imines **11** to form intermediates **85′** followed by their cyclization to intermediates **87**, which are subjected to aromatization with elimination of HNO_2 and a hydride ion. In this case, the starting β-nitrostyrene (**83a**) or atmospheric oxygen could act as the oxidant. The anions of the starting ionic liquids BF_4^- or PF_6^- served as the counterions for the pyrazolium cations in

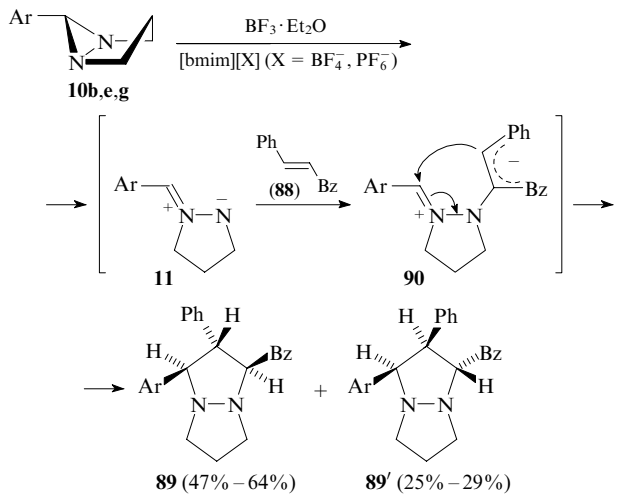
Scheme 5



Ar^1 = 4-$MeOC_6H_4$ (**b**), 4-$Pr^iC_6H_4$ (**e**), 4-MeC_6H_4 (**f**), 4-$EtOC_6H_4$ (**g**); Ar^2 = Ph, 3-$O_2NC_6H_4$, 3-$MeOC_6H_4$; X = BF_4^-, PF_6.

compounds **86**. The stereospecific formation of compounds **84** resulting in the *trans,trans*-orientation of protons in the newly formed pyrazolidine ring (see Scheme 5) was established based on the ^1H, ^{13}C and ^{15}N NMR spectroscopic data obtained with the use of ($^1H-^1H$)gNOESY, ($^1H-^{13}C$)HMBC, ($^1H-^{13}C$)HSQC and ($^1H-^{15}N$)HMBC techniques.[56, 57]

Under similar conditions (in an ionic liquid in the presence of the catalyst $Et_2O\cdot BF_3$ under slight heating), the diaziridine ring expansion in 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10b**,**e**,**g** was performed with chalcone **88**; the reaction rate decreases in the series **10b** > **10e** > **10g**. The cycloaddition of chalcone **88** to the 1,3-dipole of azomethine imine intermediate **11** was stereoselective and regiospecific and followed the mechanism of the anti-Michael addition to form two diastereomeric bicyclic structures **89** and **89′**, with diastereomer **89** prevailing. Evidently, the reaction proceeds through intermediate **90**. The three-dimensional structures of the resulting compounds were determined using the same NMR spectroscopic techniques as those used for the establishment of the structures of compounds **84**. It appeared that the protons in the pyrazolidine ring of compounds **89** are in the *trans*,*trans* orientation, whereas the corresponding protons in compounds **89′** are in the *cis*,*trans* orientation. The ratio of the diastereomers depends on the character of substituents in the aromatic moiety of the starting compounds **10**.



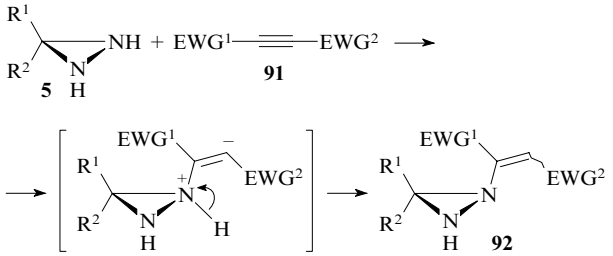
Ar	89 : 89′
4-$MeOC_6H_4$	2.3 : 1
4-$EtOC_6H_4$	6.4 : 1
4-$Pr^iOC_6H_4$	1.6 : 1

3. Reactions of diaziridines with activated alkynes

The reactions of diaziridines with activated alkynes, like the reactions with activated alkenes, may proceed with either retention of the diaziridine ring or it cleavage. Both mono- and bicyclic diaziridines can be involved in the reaction.

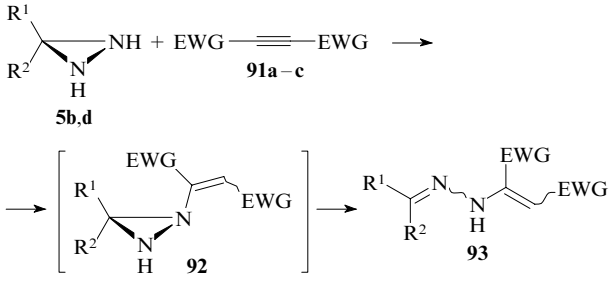
a. Reactions of monocyclic diaziridines with activated alkynes

The reactions of activated alkynes **91** with 1,2-unsubstituted diaziridines **5** in an equimolar ratio produce mono-*N*-vinyldiaziridines **92**.[65–67] In these studies, it was shown that the reactions can give either the *trans* isomer or a mixture of *cis*–*trans* isomers of *N*-vinyldiaziridines **92** depending on the nature of alkyne.



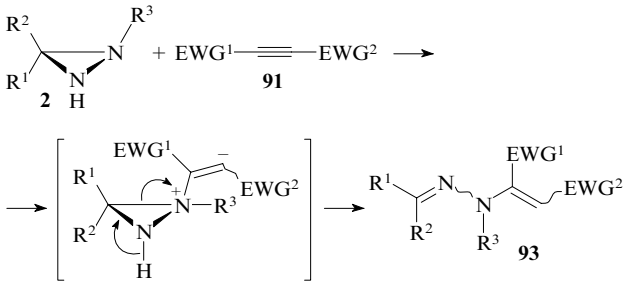
R^1, R^2 = Alk; EWG^1 = H, Bz, CF_3; EWG^2 = CO_2Me, Bz, CN, CF_3, CO_2Et, C(O)C≡CMe.

N-Vinyl derivatives **92** are prone to undergo thermal rearrangements, primarily, the diaziridine–hydrazone rearrangement, to form linear structures. In particular, *N*-vinyldiaziridines **92** synthesized by the reaction of compounds **5b**,**d** with alkynes **91a**–**c** were not isolated because, in the reaction conditions, they underwent the diaziridine–hydrazone rearrangement to produce hydrazones **93**.[65, 66, 68]



R^1-R^2 = $(CH_2)_5$ (**5b**); R^1 = Me, R^2 = Et (**5d**);
EWG = Bz (**91a**), CF_3 (**91b**), CO_2Et (**91c**).

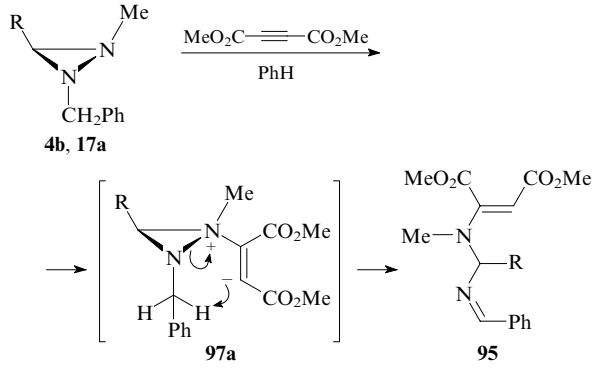
Unlike activated alkenes, alkynes **91** react with 1,3,3-trialkyldiaziridines **2** at the more basic nitrogen atom bearing the alkyl substituent due to which the resulting zwitterionic intermediates are rearranged into the corresponding hydrazones **93**.[67, 68] In the study,[67] the reaction mechanism was investigated with the use of labelled 1-methyl-3,3-pentamethylene-[2-^{15}N]-diaziridine, and it was shown that the mechanism involves the proton transfer from the nitrogen atom of the diaziridine ring accompanied by the ring opening at the C–N bond.



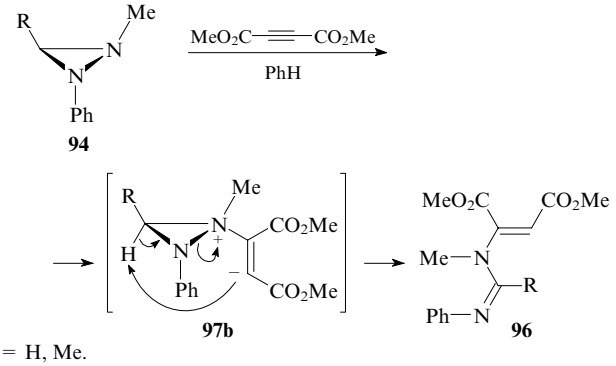
R^1, R^2, R^3 = Alk; EWG^1 = H, Me, Bz, CO_2Me;
EWG^2 = Bz, CO_2Me, CO_2Et, C(O)C≡CMe.

It was found[19] that the reaction of dimethyl acetylenedicarboxylate with 1,2-disubstituted 3-alkyldiaziridines **4b**, **17a** and **94** in benzene at room temperature produces two types of structures, **95** and **96**, depending on the nature of the substituents at the nitrogen atom. The reaction mechanism, which involves the formation of zwitterionic intermediates **97a**,**b** as the first step, was studied with the use of isotope labels. It was shown that in the case of intermediate

97a, the proton is abstracted from the α-carbon atom of the benzyl substituent, whereas in the case of 1-phenyl derivatives **94**, intermediate **97b** is stabilized *via* proton abstraction from the C(3) atom of the diaziridine ring, in both cases the ring opening occurring at the N—N bond. In the case of diaziridines **94**, the reaction is possible only with compounds containing the *cis*-methyl group at the N atom and the substituent R at the C(3) atom of the diaziridine ring. It is interesting that under similar conditions, the reactions with 1,2,3,3-tetrasubstituted diaziridines did not proceed, which was attributed to steric factors. The theoretically possible cyclization to pyrazolines was also not observed.[19]

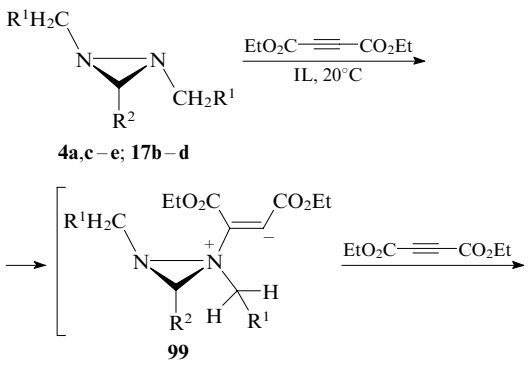


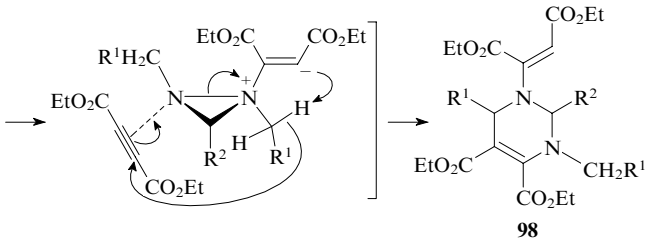
R = H (**4b**), Me (**17a**).



R = H, Me.

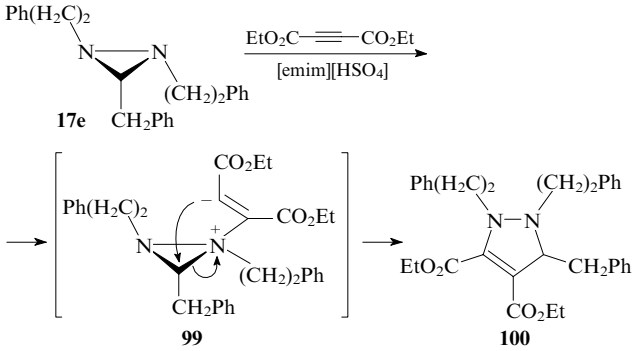
The reactions of 1,2-dialkyldiaziridines **4a**,**c**–**e** and 1,2,3-trisubstituted diaziridines **17b**–**d** with diethyl acetylenedicarboxylate (DEAD) in IL proceeded in a different way.[69] These reactions unexpectedly produced tetrahydropyrimidine derivatives **98**, *viz*., adducts of the starting diaziridine with two alkyne molecules. In the authors' opinion, the first step of the reactions of diaziridines **4** and **17** with DEAD gives dipolar intermediate **99** analogous to dipolar intermediates **97a**,**b**; however, in IL this intermediate is evidently more stable and can react with the second DEAD molecule to form tetrahydropyrimidine derivatives **98**.





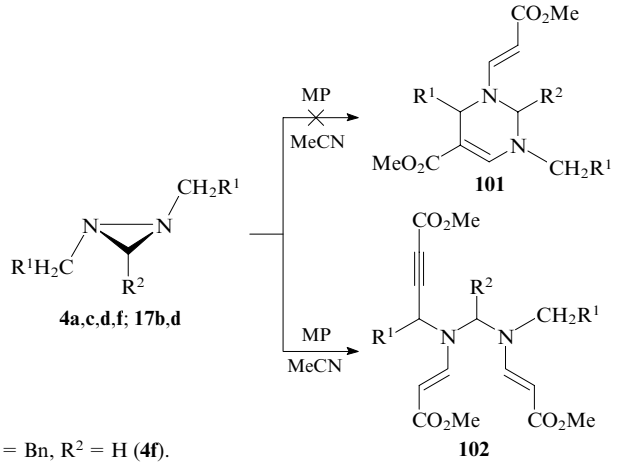
For **4**: R^2 = H: R^1 = Pr^n (**a**), Et (**c**), Me (**d**), H (**e**);
for **17**: R^1 = Me, R^2 = Et (**b**), R^1 = R^2 = Me (**c**), Et (**d**);
IL = [bmim][BF_4], [bmim][PF_6] (for R^2 = H);
[emim][HSO_4] (for R^2 = Alk).

The expected pyrazoline derivative **100** was obtained only in the reaction with 1,2-bis(2-phenylethyl)-3-benzyldiaziridine **17e** in 1-ethyl-3-methylimidazolium hydrogen sulfate ([emim][HSO_4]). Evidently, in this case the attack of the second DEAD molecule on intermediate **99** is sterically hindered and the latter is stabilized as pyrazoline derivative **100**.



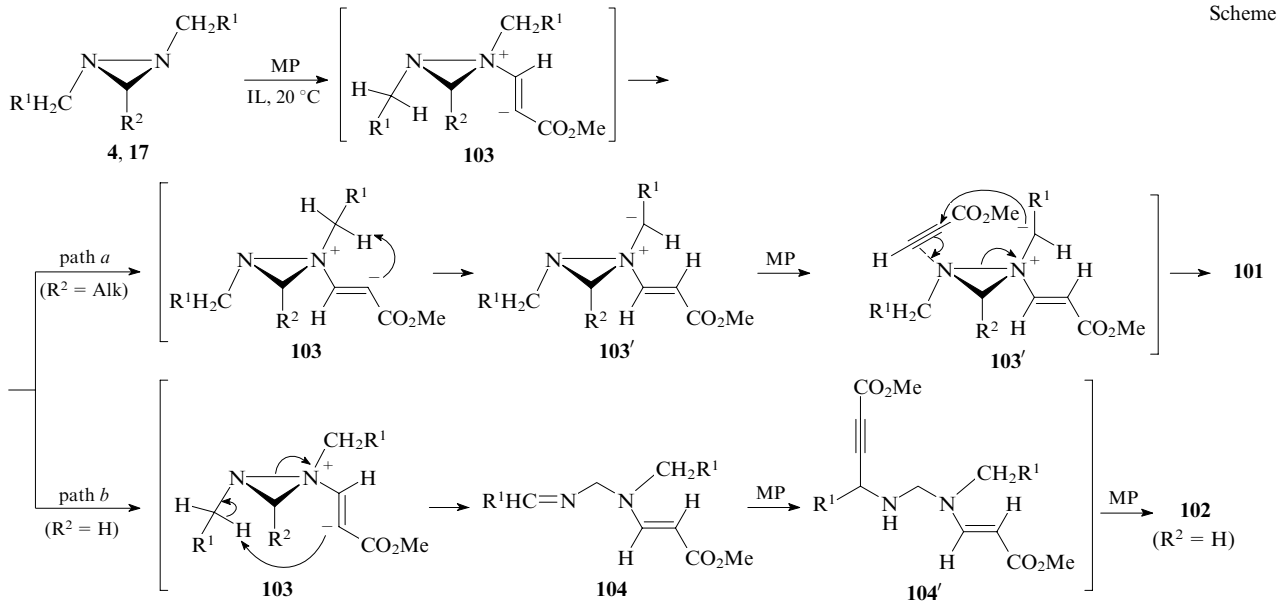
The reactions of diaziridines **4** and **17** with methyl propiolate (MP) as a representative of terminal acetylenes was performed both in organic solvents (MeCN) and ionic liquids. It appeared that the reaction in MeCN produced the previously unknown open structures **102**, which are 1 : 3 adducts of diaziridine and methyl propiolate, instead of the expected tetrahydropyrimidine derivatives **101** (Scheme 6).[70]

Scheme 6



R^1 = Bn, R^2 = H (**4f**).

Scheme 7



IL = [bmim][BF_4] (for R^2 = H), [emim][HSO_4] (for R^2 = Alk).

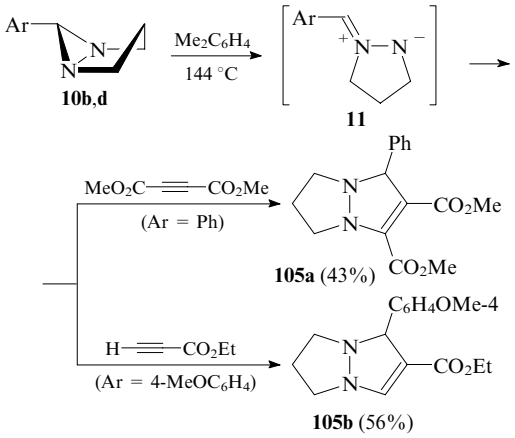
The corresponding reaction in IL produced tetrahydropyrimidine derivatives **101**; however, in some cases open structures **102** were formed as well. The reactions of diaziridines **4** proceed in [bmim][BF_4], whereas the reactions of diaziridines **17** proceed in [emim][HSO_4] (Scheme 7).

The hypothetical mechanism was proposed to explain the different behaviour of structurally similar diaziridines in the reaction with the same reagent under similar conditions (see Scheme 7). The first step of the reaction gives zwitterionic intermediate **103**, whose anion can induce proton abstraction from the α-CH_2 group of the substituent bound to any nitrogen atom. If the proton is abstracted from the α-CH_2 group of the substituent bound to the same nitrogen atom, tetrahydropyrimidine derivative **101** is then formed through intermediate **103′** (path *a*). If the proton is abstracted from the α-CH_2 group of the substituent bound to the second nitrogen atom, the reaction proceeds through intermediates **104** and **104′** to give structures **102** (path *b*).[70]

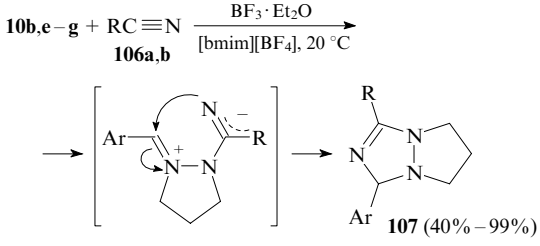
The particular pathway depends on the volume of the substituent. If the substituent is rather bulky (for example, $PhCH_2CH_2$) or the carbon atom of the diaziridine ring bears a substituent, the reaction follows the path *a*. If the volume of the substituent is not too large (for example, Bu^n or Pr^n), both paths are possible. If the substituent is small (Et), only open structures are formed even in ionic liquids. These results were confirmed by quantum chemical calculations of the energy of the transition state for 1,2-diethyl- and 1,2-bis(2-phenylethyl)diaziridines **4d**,**f** by the density functional theory (DFT) method with the use of the hybrid potential B3LYP/6-31G(d).

b. Reactions of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes with activated alkynes and nitriles under conditions of thermal and catalytic generation of azomethine imines

The thermal generation of azomethine imines **11** in the presence of dimethyl acetylenecarboxylate and ethyl propiolate by refluxing 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** in xylene afforded the corresponding 1,3-dipolar cycloaddition products **105a**,**b**, the regioselective Michael addition of ethyl propiolate being observed.[51]

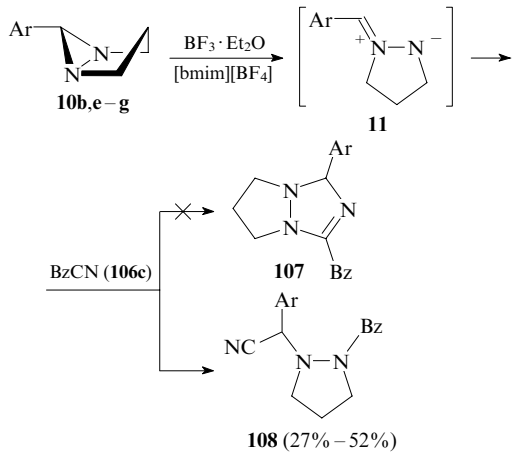


The diaziridine ring expansion in 1,5-diazabicyclo[3.1.0]hexanes **10** was performed with the use of activated nitriles **106a**,**b** in the ionic liquids [bmim][BF_4] and [bmim][PF_6] in the presence of $BF_3 \cdot Et_2O$ to form a series of annulated pyrazolidinetriazolines **107**.[71,72]

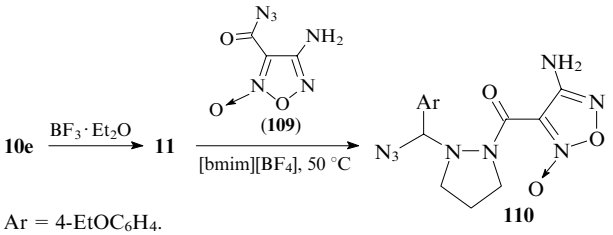


For **10**: Ar = 4-$MeOC_6H_4$ (**b**), 4-$EtOC_6H_4$ (**e**), 4-$Pr^iOC_6H_4$ (**f**), 4-MeC_6H_4 (**g**); for **106**: R = CO_2Et (**a**), CCl_3 (**b**).

Under similar conditions, the reaction of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10b**,**e**–**g** with benzoyl cyanide **106c** did not give cycloaddition products **107**. Benzoyl cyanide acted as the benzoylating agent in the reaction with the negatively charged moiety of azomethine imine **11**, and the cyanide anion was attached to the positively charged moiety to form *N*-benzoylpyrazolidine **108**.[72]



The reaction of azomethine imine **11** generated *via* diaziridine ring opening in compound **10e** was performed with azide of 4-aminofuroxanecarboxylic acid **109** in the presence of the catalyst $BF_3 \cdot Et_2O$ in IL, and the corresponding acylated pyrazolidine **110** was obtained. In MeCN, the reaction was not observed.[72]



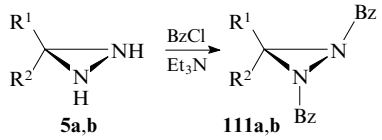
Ar = 4-$EtOC_6H_4$.

VII. Reactions of diaziridines with acylating agents

1. Acylation of monocyclic diaziridines

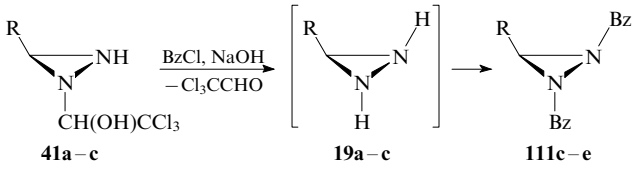
Acylation reactions are known only for 1- and 1,2-unsubstituted diaziridines. Generally, the resulting *N*-acyl derivatives of diaziridines are extremely labile and prone to various rearrangements accompanied by the diaziridine ring opening. The rearrangement pathways are determined by the structures of the starting diaziridines. Hence, *N*-acyldiaziridines are considered as interesting precursors for the synthesis of other classes of heterocyclic compounds.

First 1,2-diacyl derivatives of diaziridines **111a**,**b** were synthesized by Schmitz, who used the reactions of 3,3-dialkyldiaziridines **5a**,**b** with benzoyl chloride in the presence of triethylamine.[6]



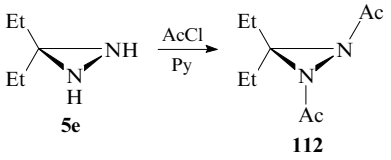
$R^1 = R^2$ = Me (**a**, 87%), $R^1 - R^2 = (CH_2)_5$ (**b**, 99%).

3-Alkyldiaziridines **19a**–**c** were characterized in the form of 1,2-dibenzoyl derivatives, because the isolation of compounds **19a**–**c** produced by classical methods is difficult. For example, 1,2-dibenzoyldiaziridines **111c**–**e** were isolated in the reactions of benzoyl chloride with the corresponding choral hydrate derivatives of diaziridines **41a**–**c** under alkaline conditions.[73, 74]

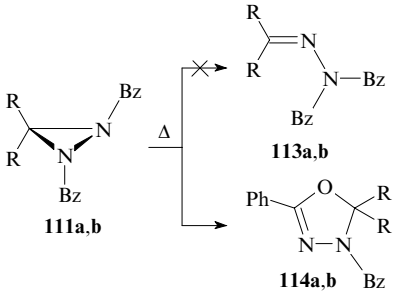


Compound **111**	R	Yield (%)
c	Me	91.5
d	Pr^n	72
e	Bu^t	89

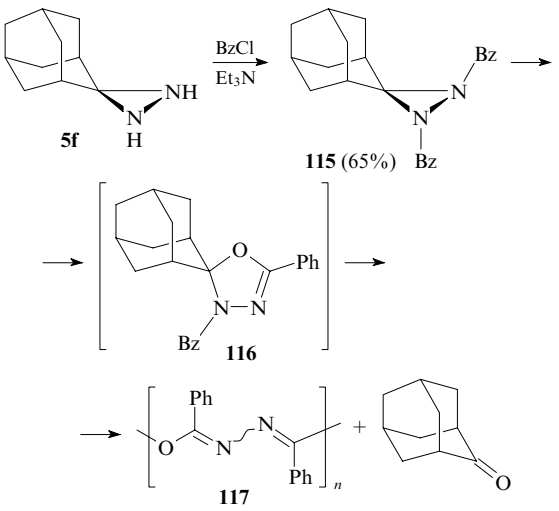
The simplest unsubstituted diaziridine was also characterized in the form of the dibenzoyl derivative.[75] Paulsen [76] synthesized 1,2-diacetyl-3,3-diethyldiaziridine **112** by the acetylation of 3,3-diethyldiaziridine (**5e**) by acetyl chloride in the presence of pyridine.



As mentioned above, 1,2-diacyl derivatives of diaziridines relatively easily undergo isomerization. It was shown that the rearrangement of 3,3-dialkyl-1,2-dibenzoyldiaziridines **111a**,**b** produces oxadiazolines **114a**,**b** rather than hydrazones **113a**,**b**.[77]

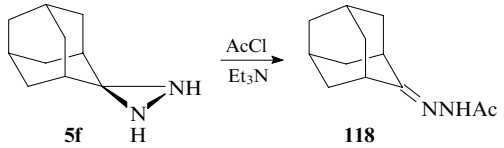


The reaction of spiro(adamantane-2,3′-diaziridine) (**5f**) with two equivalents of benzoyl chloride gives dibenzoyl derivative **115**, which particularly easily decomposes in the presence of traces of acids. During storage compound **115** is rearranged through the formation of oxadiazoline **116** to



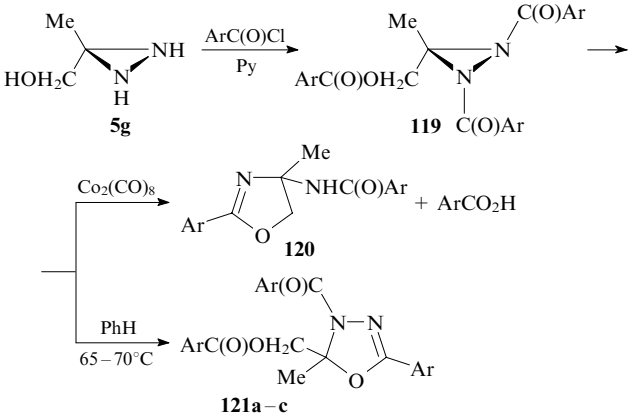
give polymer **117** and free adamantanone as the final products.

Adamantanone *N*-acetylhydrazone (**118**) was isolated as the only product in the reaction of diaziridine **5f** with acetyl chloride.[78]



5f **118**

Tris(aroyl) derivatives **119** were synthesized[79] by the complete aroylation of 3-hydroxymethyl-3-methyldiaziridine (**5g**). It was shown that in the presence of dicobalt octacarbonyl in benzene, compounds **119** are rearranged into oxazolines **120** upon heating, whereas the thermal rearrangement in the absence of the catalyst affords 1,3,4-oxadiazolines **121**, which are not transformed into oxazolines **120** after the addition of the catalyst.

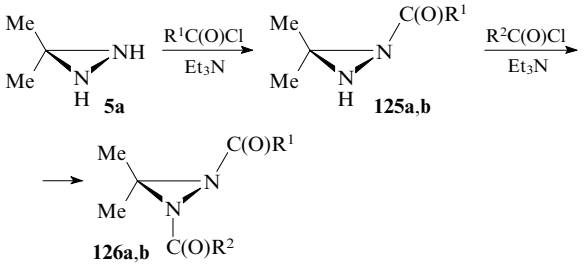


5g **119** **120** **121a–c**

Ar = 4-XC_6H_4 [X = Me (**a**, 79%), MeO (**b**, 59%), Cl (**c**, 79%)].

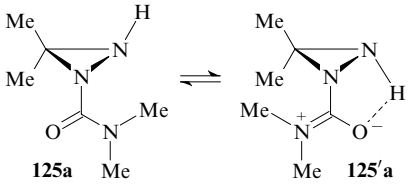
The acylation of the spirocyclic derivative of glucose and diaziridine **122a** gives the corresponding hydrazone derivatives **123a**,**b** (Scheme 8).[80] The reaction with benzoyl chloride produces also 1,3,4-oxadiazoles **124a**,**b**. Studies using ^{15}N-labelled diaziridines showed that the reaction proceeds predominantly at the pseudo-equatorial nitrogen atom of the spiro-diaziridine system.

1-Acyldiaziridines **125a**,**b** were synthesized by the acylation of 3,3-dimethyldiaziridine (**5a**),[26,81] and the kinetics of the inversion of these compounds was studied by NMR spectroscopy. Unsymmetrical 1,2-bis(acyl)diaziridines **126a**,**b** were synthesized by the secondary acylation of diaziridines **125**. *cis*-Isomer **125′a** stabilized by an intramolecular hydrogen bond was detected.



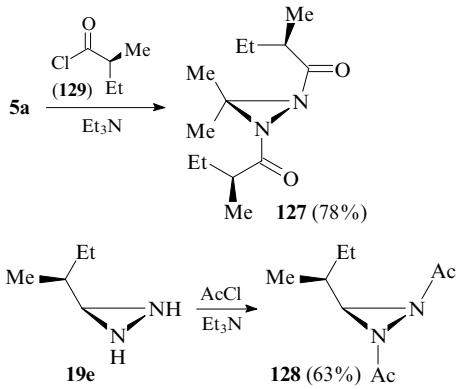
5a **125a**,**b** **126a**,**b**

For **125**: $R^1 = NMe_2$ (**a**, 35%), OMe (**b**, 51.6%);
for **126**: $R^1 = NMe_2$; R^2 = Ph (**a**, 92%), OMe (**b**, 37.5%).



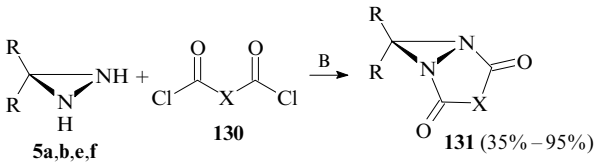
125a **125′a**

The synthesis of 1,2-bis(acyl)diaziridines **127** and **128** with the use of enantiomerically pure acyl chloride **129** and diaziridine **19e**, respectively, was described.[82]



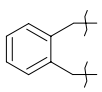
5a **127** (78%) **19e** **128** (63%)

The acylation of 3,3-dialkyldiaziridines **5** by dicarboxylic acid bis(chlorides) **130** affords cyclic 1,2-bis(acyl)diazi-

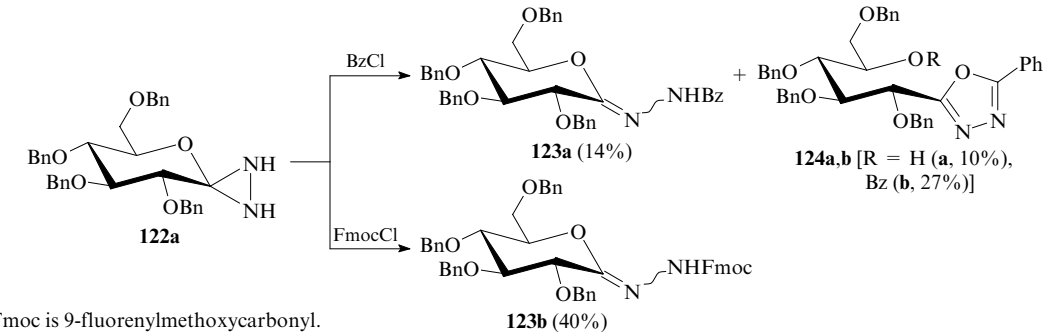


5a,**b**,**e**,**f** **130** **131** (35%–95%)

R = Me (**a**), Et (**e**), Pr^n (**f**); R–R = $(CH_2)_5$ (**b**);

X = , $(CH_2)_2$, , , *etc.*

Scheme 8

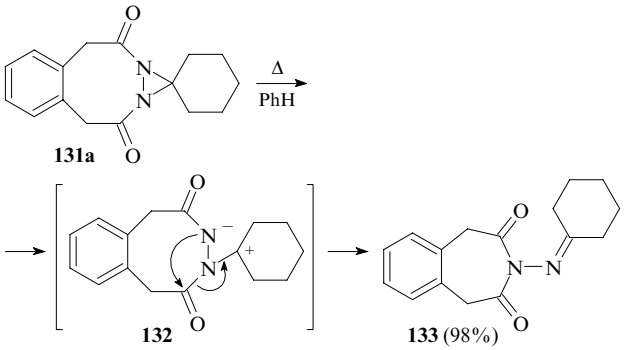


122a **123a** (14%) **124a**,**b** [R = H (**a**, 10%), Bz (**b**, 27%)] **123b** (40%)

Fmoc is 9-fluorenylmethoxycarbonyl.

ridines **131**;[30] however, they are thermally unstable and are easily transformed into other heterocyclic systems.[30, 67, 83]

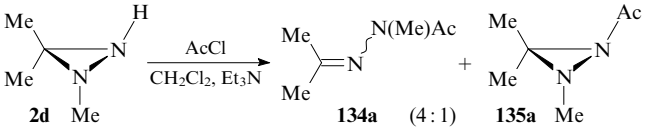
For example, the heating of compound **131a** leads to C–N bond cleavage in the diaziridine ring to form 1,3-dipolar structure **132** stabilized in the form of cyclic hydrazone **133**.[83]



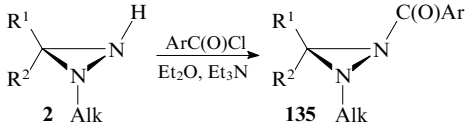
In the presence of various dipolarophiles (enamines, ynamines,[30] nitrones[84]), intermediates **132** can be involved in 1,3-dipolar cycloaddition reactions.

N-Monoalkyldiaziridines **1** and **2** behave as ambident nucleophiles toward acyl chlorides. The attack of the acylating agent can occur both on the alkylated and unsubstituted nitrogen atoms. The attack on the alkylated nitrogen atom results in the formation of *N*-acylhydrazones **134**, whereas the acylation at the unsubstituted nitrogen atom gives *N*-acyldiaziridines **135** (Scheme 9).

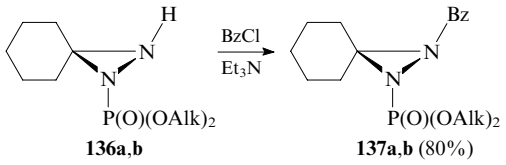
The model reaction of 1,3,3-trimethyldiaziridine **2d** with acetyl chloride was studied[38] to determine the regioselectivity of acylation of *N*-monoalkyldiaziridines. The ^{1}H NMR spectroscopic study of the reaction mixture showed that *N*-acetylhydrazone **134a** and *N*-acetyldiaziridine **135a** are formed in a ratio of 4 : 1, which remains unchanged during storage and after the addition of triethylammonium chloride, which excludes the possibility of the diaziridine–hydrazone rearrangement under the reaction conditions. It was suggested that the attack of the acylating agent occurs predominantly on the alkylated nitrogen atom, which is more nucleophilic, as was confirmed by quantum chemical calculations.[38]



However, the pathway of the acylation of *N*-monoalkyldiaziridines **2** depends on the nature of the acylating agent as well. Thus, the reactions with aroyl chlorides gave *N*-aroyldiaziridines **135** as the major products in relatively high yields.[30, 78]

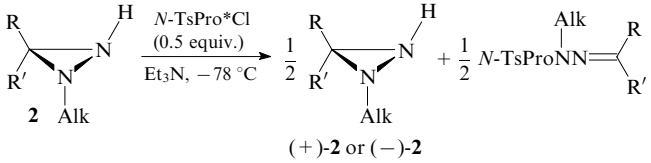


The reaction of benzoyl chloride with phosphorylated diaziridines **136a**,**b** produced the corresponding benzoylated derivatives **137a**,**b**. In this case, the attack of the acylating agent also occurs on the unsubstituted nitrogen atom of diaziridines.[85]



Alk = Et (**a**), Pr^n (**b**).

The research group headed by Kostyanovsky developed a simple and efficient method for the optical activation of 1,3,3-trialkyldiaziridines **2** based on the acylation of diaziridines. For example, enantiomers **2*** can be synthesized with an optical purity of 10%–75% by the reaction of 0.5 equiv. of (*S*)- or (*R*)-*N*-tosylprolyl chloride (*N*-TsPro*Cl) with the corresponding racemic diaziridines **2**.[36, 38, 39, 86–89] For this purpose, (*S*)-2,4-dinitrophenylprolyl chloride was also used.[40]

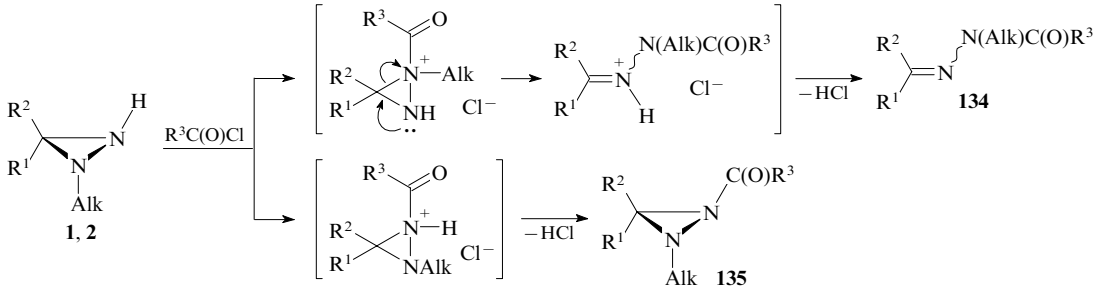


Alk	R′	R	Alk	R′	R
Me	$(CH_2)_4$		Me	Me	Me (**2d**)
$(CH_2)_2NMe_2$	Me	Me (**2b**)	Me	Ad′	
Bn	Me	Me	Bu^n	Me	Me
$(CH_2)_2Ac$	Me	Me	$(CH_2)_3$		CF_3
$(CH_2)_3$		Me	$(CH_2)_3$		CO_2Me

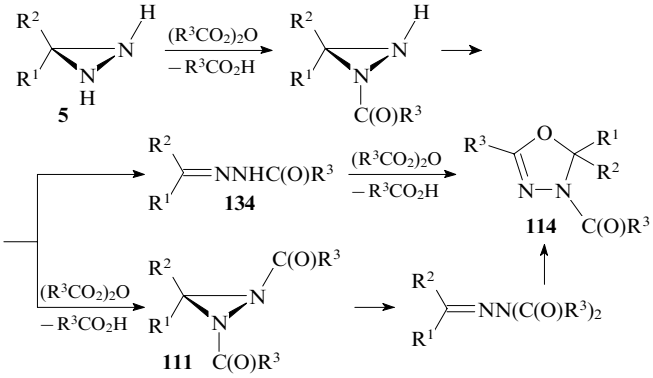
Ad′ is an adamantane fragment without one CH_2 group.

The reactions of 1,2-unsubstituted diaziridines with acid anhydrides also involve the acylation of the nitrogen atoms as the first step; however, in all cases the resulting *N*-acyl-

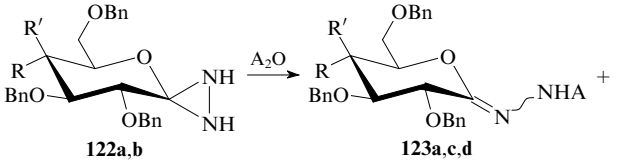
Scheme 9

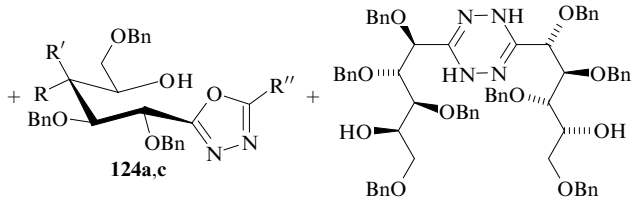


diaziridines are transformed into other heterocyclic systems under the reaction conditions. For example, 3,3-dialkyldiaziridines **5** are transformed into the corresponding 1,3,4-oxadiazolines **114** on heating with an excess of carboxylic acid anhydrides.[90,91] Two pathways for the formation of oxadiazolines were proposed in these studies: through 1,2-diacyldiaziridines **111** or monoacylhydrazones **134**. The possible contribution of both pathways to the mechanism of the formation of products **114** was shown.



The acylation of 1,2-unsubstituted spiro derivatives of D-glucose and D-galactose and diaziridine (**122a**,**b**) by acetic and benzoic anhydrides affords the corresponding hydrazone derivatives **123a**,**c**,**d**.[90] 1,3,4-Oxadiazoles **124a**,**c** and dihydrotetrazine **138** were isolated as by-products. As in the case of acyl chlorides, studies with the use of ^{15}N-labelled diaziridines showed that the D-galactose derivative is acylated predominantly at the pseudo-equatorial nitrogen atom of the spiro-diaziridine system, whereas the D-glucose derivative is acylated predominantly at the pseudo-axial nitrogen atom.





138 (for **122b** and Ac_2O, 6%)

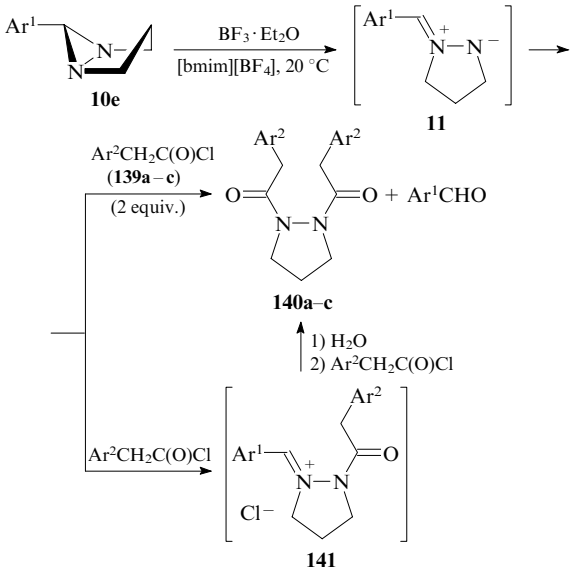
R = OBn, R′ = H (**122a**); R = H, R′ = OBn (**122b**).

Compound	A	R	R′	R″	Yield (%)
123a	Bz	OBn	H		61
123c	Ac	OBn	H		70–80
123d	Ac	H	OBn		65–83
124a		OBn	H	Ph	8
124c		H	OBn	Me	5–9

The formation of by-products **124** was attributed to the 1,5-cyclization of *N*-acylazomethine imine intermediates, and the formation of product **138** was accounted for by the acid-catalyzed rearrangement of the starting diaziridines into the corresponding hydrazones followed by the dimerization.

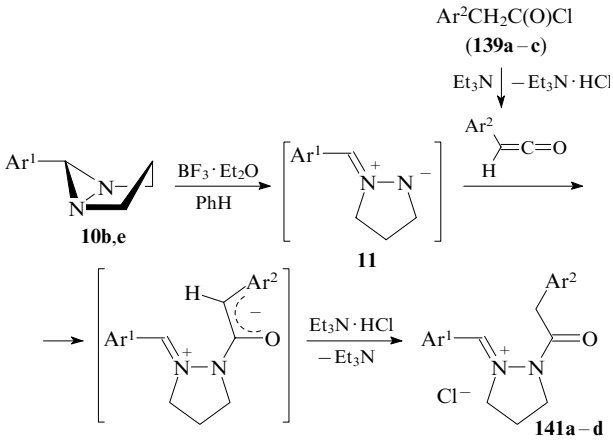
2. Reactions of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes with acylating agents

6-Aryl-1,5-diazabicyclo[3.1.0]hexanes **10** were not introduced into the reaction with acyl chlorides. However, the reactions of arylacetyl chlorides **139a–c** with azomethine imines **11**, which were generated by the catalytic opening of the diaziridine ring in compounds **10** in IL in the presence of a catalytic amount of $BF_3 \cdot Et_2O$, resulted in the addition of arylacetyl moieties of two molecules of arylacetyl chlorides **139** to a molecule of azomethine imine **11** to form 1,2-bis(arylacetyl)pyrazolidines **140a–c**. Apparently, the mechanism of the formation of compounds **140** involves the acylation of the negative pole of azomethine imine intermediate **11** as the first step to form second intermediate **141** followed by the elimination of the aldehyde moiety in the presence of traces of water in the solvent and the subsequent acylation at the second nitrogen atom.[92]



Ar^1 = 4-$EtOC_6H_4$; Ar^2 = Ph (**a**), 4-MeC_6H_4 (**b**), 2,4-$(O_2N)_2C_6H_3$ (**c**).

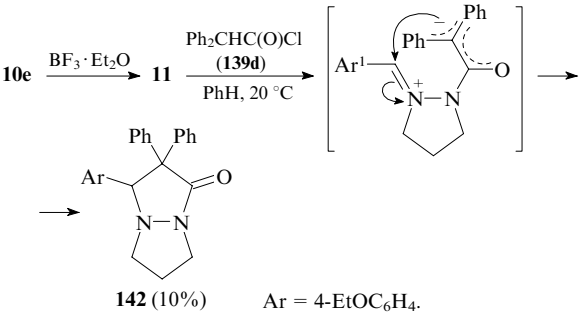
Compounds **141a–d**, which are analogues of chloromethylamine, were synthesized by the same reaction in the



For **139**: Ar^2 = Ph (**a**), 4-MeC_6H_4 (**b**), 2,4-$(O_2N)_2C_6H_3$ (**c**);
for **141**: Ar^2 = Ph: Ar^1 = 4-$MeOC_6H_4$ (**a**), 4-$EtOC_6H_4$ (**b**);
Ar^1 = 4-$EtOC_6H_4$: Ar^2 = 4-MeC_6H_4 (**c**), 2,4-$(O_2N)_2C_6H_3$ (**d**).

absence of traces of water (in anhydrous benzene under an argon flow) and in the presence of triethylamine taken in an equimolar amount with respect to arylacetyl chlorides **139**.[92] Under these conditions, aryl ketenes apparently act as acylating agents.

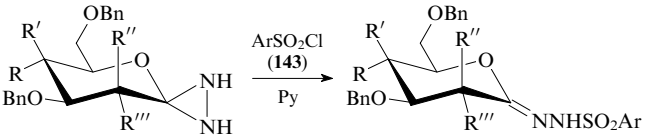
Bicyclic compound **142** was produced in low yield by the reaction of azomethine imine **11** (Ar = 4-$EtOC_6H_4$) with diphenylacetyl chloride **139d** in benzene both in the absence and in the presence of triethylamine.[92]



142 (10%) Ar = 4-$EtOC_6H_4$.

3. Reactions of diaziridines with sulfonyl chlorides

The reactions of 1,2-unsubstituted diaziridines, in particular, of 1,2-unsubstituted spirocyclic derivatives **122**, with sulfonyl chlorides **143** were studied in detail.[80] The reactions of D-glucose, D-galactose and D-mannose derivatives **122a–c** with sulfonyl chlorides **143** in pyridine produced sulfonylated hydrazones **144**.

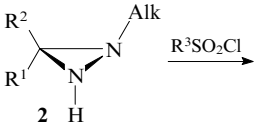


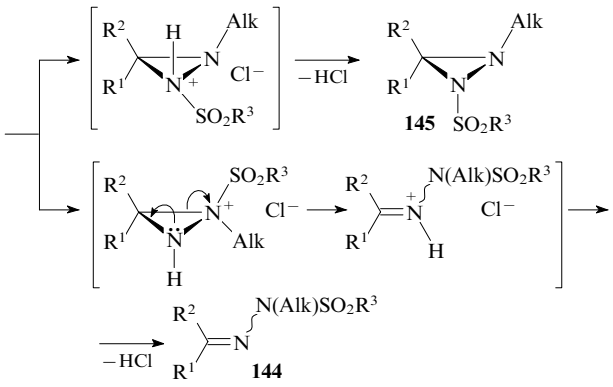
122a–c **144** (55%–83%)

R″ = H, R‴ = OBn: R = OBn, R′ = H (**a**); R = H, R′ = OBn (**b**);
R = OBn, R′ = H, R″ = OBn, R‴ = H (**c**);
Ar = 4-MeC_6H_4, 2,4,6-$Pr^i_3C_6H_2$, 2-Naph.

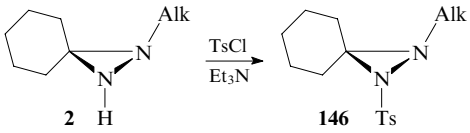
Studies with the use of ^{15}N-labelled diaziridines showed that the sulfonylation of galactose derivative **122b** proceeds predominantly at the pseudo-equatorial nitrogen atom of the spiro-diaziridine system, whereas the sulfonylation of glucose derivative **122a** proceeds at the pseudo-axial nitrogen atom. The formation of bis- or monosulfonylated diaziridines was observed in none of the cases (even in the presence of an excess of sulfonyl chlorides), which is evidently associated with the ease of the diaziridine–hydrazone rearrangement under the reaction conditions.

As in the reactions with acylating agents, *N*-monoalkyldiaziridines **2** behave as ambident nucleophiles toward sulfonyl chlorides. The attack can occur on both nitrogen atoms to form *N*-sulfonyldiaziridines **145** and *N*-sulfonylhydrazones **144**. The reaction pathway depends, as a rule, on the type of substitution at the C(3) atom of the starting diaziridine.[80, 93]





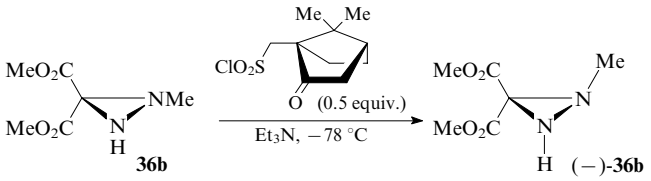
The reactions of 1-alkyl-3,3-pentamethylenediaziridines **2** with TsCl in the presence of triethylamine produce the corresponding 1-alkyl-2-tosyl-3,3-pentamethylenediaziridines **146** in good yields.[93]



2 **146**

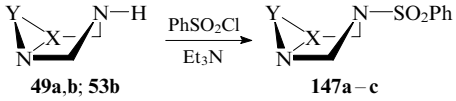
Alk = Me (57%), Et (71%), Pr^n (52%).

The kinetic enantiomeric enrichment of dimethyl 1-methyldiaziridine-3,3-dicarboxylate **36b** is based on the reaction of this diaziridine with D-10-camphorsulfonyl chloride. The reaction produced the enriched (−)-form of diaziridine **36b** (5.27% *ee*), but the product of its subsequent transformation in the reaction with D-10-camphorsulfonyl chloride was not detected.[36, 94]



36b (−)-**36b**

The reactions of monocyclic 1,2-dialkyldiaziridines with sulfonyl chlorides were not described in the literature. However, the reactions of bicyclic 1,2-dialkyldiaziridines (1,3,5- and 1,3,6-triazabicyclo[3.1.0]hexanes) containing the NH group in the bicyclic system with phenylsulfonyl chloride were reported. The latter reaction proceeds exclusively at the NH group of the five-membered ring to form phenylsulfonyl derivatives **147**, the nitrogen atoms of the diaziridine ring remaining intact.[28, 32]

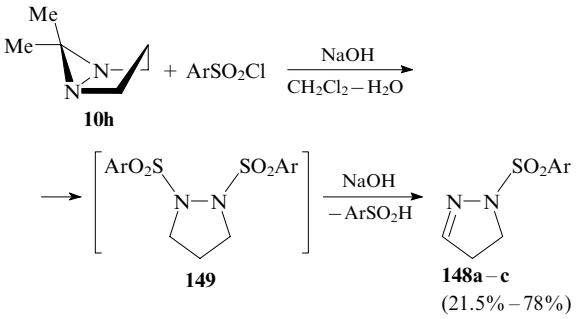


49a,b; **53b** **147a–c**

Compound **147**	X	Y	Yield (%)
a	N	CHMe	80
b	N	CHEt	81
c	CMe	NMe	58

The reactions of 6,6-dimethyl-1,5-diazabicyclo[3.1.0]-hexane (**10h**) with arylsulfonyl chlorides in the presence of inorganic bases produced 1-arylsulfonylpyrazolines **148**. Evidently, 1,2-bis(arylsulfonyl)pyrazolidines **149** are formed

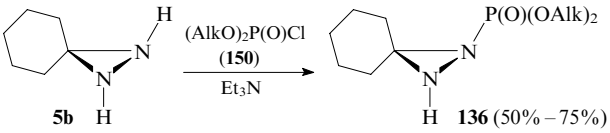
in the first step followed by their transformation into compounds **148** with a loss of the sulfinic acid moiety in a strongly alkaline medium.[95, 96]



For **148**: Ar = 4-MeC_6H_4 (**a**), 4-FC_6H_4 (**b**), 4-BrC_6H_4 (**c**).

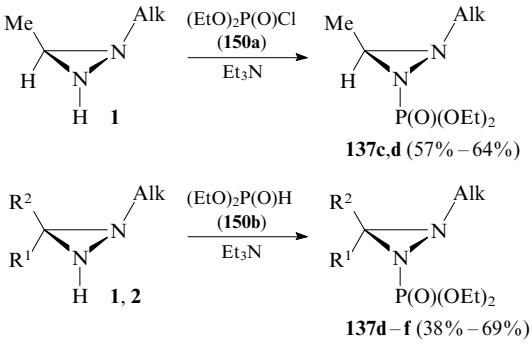
4. Reactions of diaziridines with phosphorus acid derivatives

The reactions of 3,3-pentamethylenediaziridine **5b** with an equimolar amount of dialkyl phosphorochloridate **150** in the presence of triethylamine give 1-dialkylphosphono-3,3-pentamethylenediaziridines **136** in high yields [85] An increase in the amount of the phosphorylating agent does not lead to the formation of bisadducts.



Alk = Me, Et, Pr^n, Bu^n.

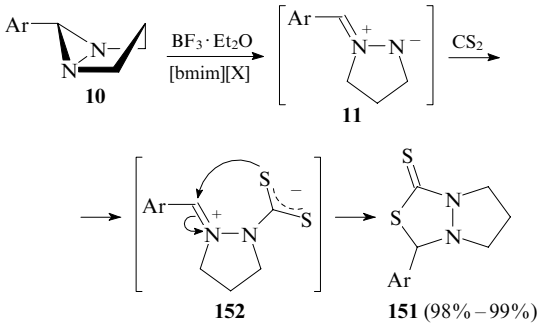
In the reactions of *N*-monoalkyldiaziridines **1** and **2** with diethyl phosphorochloridate (**150a**) and diethyl phosphite (**150b**), the phosphorylation occurs at the unsubstituted nitrogen atom of the diaziridine ring to form phosphorylated diaziridines **137** (the modified Todd–Atherton method).[97]



Compound **137**	R^1	R^2	Alk
c	H	Me	Me
d	H	Me	Bu^n
e	H	Me	Et
f	Me	Me	Pr^i

5. Reactions of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes with carbon disulfide

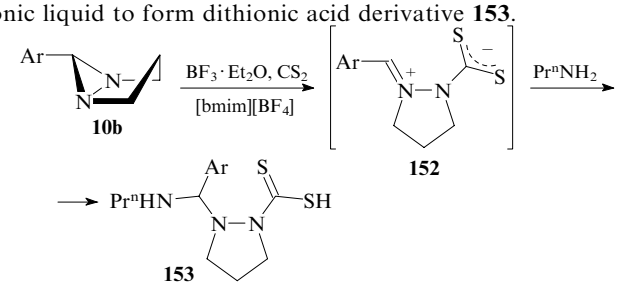
The reactions of diaziridines with carbon disulfide can also be assigned to thioacylation reactions. Carbon sulfide does not react with monocyclic diaziridines; however, it was introduced into the reaction with azomethine imines **11** generated from 6-aryl-1,5-diazabicyclo[3.1.0]hexanes **10** in the presence of the catalyst $BF_3 \cdot Et_2O$ in the ionic liquid [bmim][BF_4]([PF_6]) to form 3-aryldihydro-5*H*-pyrazolo-[1,2-*c*][1,3,4]thiadiazole-1-thiones **151**.[72, 98]



Ar = 4-YC_6H_4 (Y = MeO, EtO, Pr^iO, Me, Cl); X = BF_4, PF_6.

The formation of new intermediates was detected by TLC monitoring of these reactions. In one case (for Y = Me), the intermediate was isolated in the individual state and characterized by ^1H and ^{13}C NMR spectroscopy and elemental analysis. The structure of 2-(4-methylbenzylidene)pyrazolidin-2-ium 1-carbodithioate (**152**, Ar = 4-MeC_6H_4) was assigned to this compound. Zwitterions **152** exist over a long period of time in an ionic liquid (TLC monitoring), being partially transformed into final bicyclic compounds **151**, but they undergo fast cyclization in organic solvents.

Zwitterion **152** (Ar = 4-$MeOC_6H_4$) was trapped by performing the *in situ* reaction with n-propylamine in an ionic liquid to form dithionic acid derivative **153**.



Ar = 4-$MeOC_6H_4$.

VIII. Reactions of diaziridines with heterocumulenes

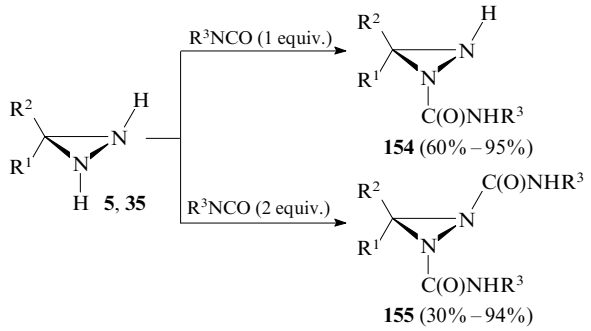
Among different types of heterocumulenes, isocyanates, isothiocyanates and ketenes were studied in reactions with diaziridines. Both adducts with retention of the diaziridine ring and the ring opening and expansion products can be obtained depending on the degree of substitution of the staring diaziridine and the nature of the heterocumulene.

1. Reactions of diaziridines with isocyanates and isothiocyanates

a. Reactions of monocyclic diaziridines with isocyanates and isothiocyanates

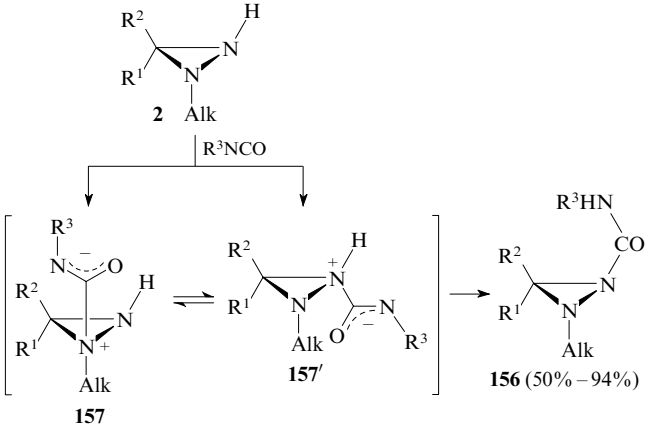
1,2-Unsubstituted diaziridines **5** and **35** are acylated by isocyanates to form mono- and biscarbamoyl derivatives **154** and **155**, respectively, depending on the diaziridine to isocyanate ratio (Scheme 10).[7, 26, 78, 81, 99–101]

Scheme 10



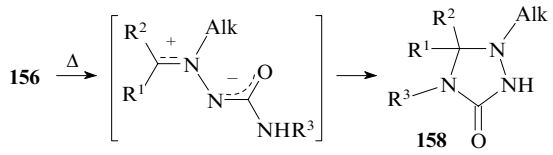
R^1 = Me, CO_2Me; R^2 = Me, CO_2Me, CH_2OH, $(CH_2)_2NEt_2$, $CH(OH)C(OH)Me_2$; $R^1 - R^2$ = $(CH_2)_5$, $(CH_2)_6$, Ad′; R^3 = Ph, Me, Pr^n, Bu^n, Et, cyclo-C_6H_{11}, (*S*)-CHPhMe.

As opposed to acyl chlorides, the reactions of isocyanates with *N*-monoalkyldiaziridines **2** produce only *N*-carbamoyldiaziridines **156**.[11, 26, 36, 38, 78, 102, 103] Shustov suggested[36] that in this case, the attack of the electrophile occurs predominantly on the more basic alkylated nitrogen atom of the diaziridine ring; however, the resulting zwitterionic adduct **157**, which is more stable than the acyldiaziridinium cation, is in equilibrium with isomeric zwitterion **157′**. The latter is stabilized *via* a proton migration and gives *N*-carbamoyldiaziridines **156**. However, the initial attack of isocyanate on the unsubstituted nitrogen atom cannot be ruled out.

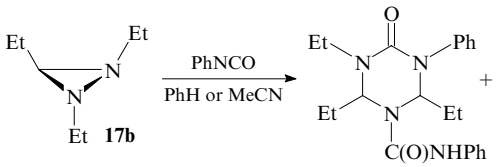


R^3 = Ph, Me, Pr^n, Bu^n, (*S*)-CHPhMe.

Generally, *N*-carbamoyldiaziridines **156** are thermally unstable and are transformed into 1,2,4-triazolidin-3-ones **158** *via* C – N bond cleavage in the diaziridine ring.[78, 102, 103]



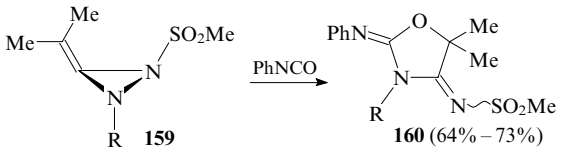
The reactions of 1,2,3-triethyldiaziridine (**17b**) with phenyl isocyanate are nonselective and are accompanied by the diaziridine ring opening to form a mixture of products.[104]



+ PhNHC(O)NEtC(O)Et + PhNHC(O)NHEt +

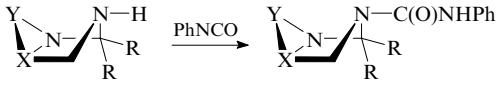
+ EtNHC(O)NPhC(O)NHPh

It was found[105] that the reaction of phenyl isocyanate with alkylidenediaziridines **159** at room temperature produces oxazolidines **160**.



$R = 4\text{-}XC_6H_4$ (X = H, Me, Br).

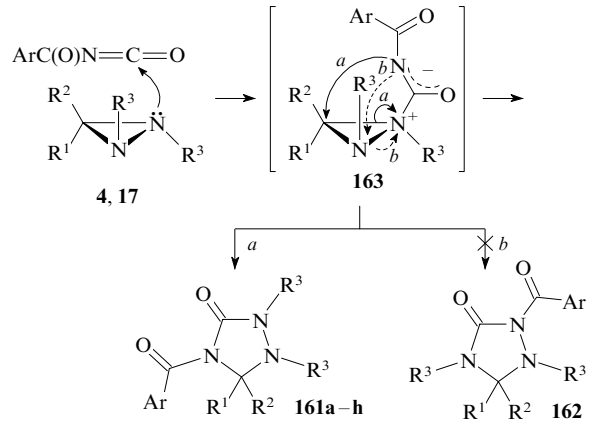
Among other reactions of representatives of 1,2-disubstituted diaziridines with isocyanates, let us mention the carbamoylation of the NH group in the five-membered ring of bicyclic diaziridines **49c** and **54e** with the nitrogen atoms of the diaziridine ring remaining intact to form adducts **49d** and **54f**, respectively.[35, 106]



Y = CH_2, X = N, R = H (**49**); Y = NMe, X = CMe, R = Me (**54**).

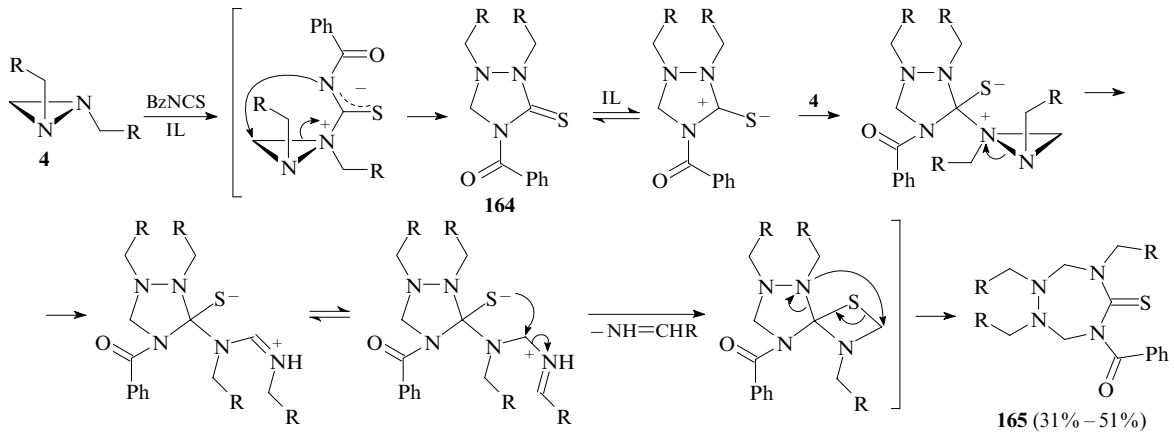
4-Aroyl-1,2,4-triazolidin-3-ones **161** were isolated in the reactions of 1,2-di (**4**), 1,2,3-tri- (**17**) and 1,2,3,3-tetraalkyldiaziridines with aroyl isocyanates, which are more reactive

Scheme 11



Compound **161**	R^1	R^2	R^3	Ar	Yield (%)
a	H	H	Et	Ph	37
b	H	H	Pr^n	Ph	34
c	H	H	Bu^n	Ph	46
d	H	H	Et	4-ClC_6H_4	43
e	Me	H	Et	Ph	30
f	Et	H	Et	Ph	44
g	Me	Me	Et	4-ClC_6H_4	21
h	$(CH_2)_5$		Me	4-ClC_6H_4	37

Scheme 12



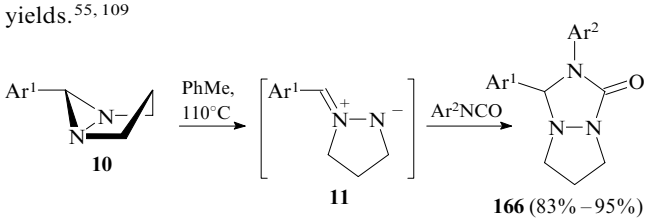
R = Me, Et, Pr^n, Ph; IL = [emim][BF_4], [emim][PF_6].

than aryl isocyanates (Scheme 11, path *a*).[104, 107] According to the X-ray diffraction data for compound **161a**, these compounds have the above-mentioned structure but are not isomeric 2-aroyl-1,2,4-triazolidin-3-ones **162** (path *b*).[107] The reaction proceeds only on heating (60 – 80 °C) and involves, apparently, the formation of zwitterionic intermediate **163** as the first step followed by the attack of the conjugated anion on the carbon atom of the diaziridine ring with the simultaneous C – N bond cleavage (see Scheme 11, path *a*).

The investigation of the reaction of 1,2-dialkyldiaziridines **4** with benzoyl isothiocyanate in various organic solvents at different temperatures showed[108] that this reaction is extremely nonselective (at high temperatures) or does not proceed at all. This reaction proved to be quite selective only when it was performed in IL ([emim][BF_4] or [emim][PF_6]). However, the reaction produced the previously unknown unfused tetrazepane-5-thione derivatives **165** rather than the expected 4-benzoyl-1,2,4-triazolidine-3-thiones **164**. It was hypothesized that 4-benzoyl-1,2,4-triazolidine-3-thiones **164** are formed in the first step; however, these compounds undergo transformations under the reaction conditions. The probable mechanism is shown in Scheme 12.

b. Reactions of 6-aryl-1,5-diazabicyclo[3.1.0]hexanes with isocyanates and isothiocyanates

The reactions of 1,5-diazabicyclo[3.1.0]hexane derivatives with isocyanates and isothiocyanates were not performed, but the reactions of these reagents with azomethine imines **11** thermally generated from 6-aryl-1,5-diazabicyclo[3.1.0]-hexanes **10** (refluxing in toluene) were studied in considerable detail. It was shown that the 1,3-dipolar cycloaddition of aryl isocyanates and aryl isothiocyanates to azomethine imines **11** is highly regioselective and gives substituted perhydropyrazolo[1,2-*a*][1,2,4]triazoles **166** in high yields.[55, 109]



Ar^1, Ar^2 = Ph, 4-ClC_6H_4, 4-$MeOC_6H_4$, 1-Naph.

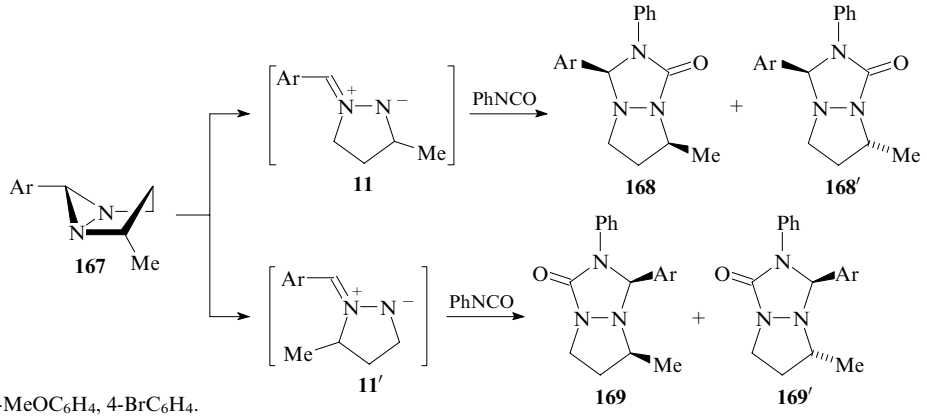
The thermolysis of 6-aryl-2-methyl-1,5-diazabicyclo[3.1.0]hexanes **167** in the presence of phenyl isocyanate is nonselective and produces a mixture of all possible regio- and stereoisomers **168**, **168′** and **169**, **169′**, which are formed as a result of the reaction of two isomeric azomethine imines **11** and **11′** (Scheme 13).[110]

2. Reactions of diaziridines with ketenes

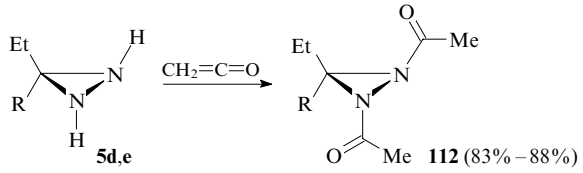
a. Reactions of monocyclic diaziridines with ketenes

Paulsen[76] showed that the bubbling of the simplest ketene through a solution of diaziridines **5d**,**e** affords 1,2-diacetyl derivatives **112**.

Scheme 13

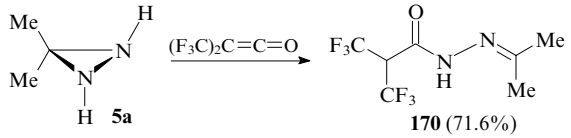


Ar = 4-$MeOC_6H_4$, 4-BrC_6H_4.

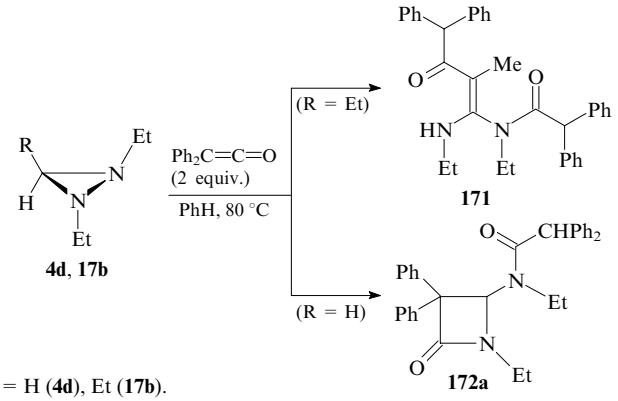


R = Me (**d**), Et (**e**).

Attempts to acylate 3,3-dimethyldiaziridine (**5a**) by bis(trifluoromethyl) ketene led to the formation of isomeric hydrazone **170**.[26]



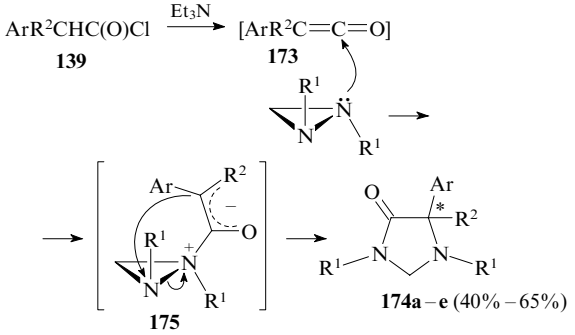
The reactions of 1,2-dialkyldiaziridines **4** and 1,2,3-trialkyldiaziridines **17** with ketenes were studied for the first time by the research group headed by Komatsu in 1974 using the reaction with diphenyl ketene as an example.[104] It was found that, in refluxing benzene, one molecule of the starting dialkyldiaziridine reacts with two diphenyl ketene molecules. The reaction is accompanied by the N—N bond cleavage in the diaziridine ring to form compounds, whose structures depend on the type of substitution at the carbon atom in the starting diaziridine. The reaction of 1,2,3-trialkyldiaziridine **17b** produced acyclic adduct **171**, whereas the reaction of 1,2-diethyldiaziridine (**4d**) gave β-lactam **172a**.



R = H (**4d**), Et (**17b**).

With the aim of finding other possible transformations of 1,2-dialkyldiaziridines that occur in the reactions with ketenes, these reactions were systematically studied for ketenes with different structures (mono- and diaryl ketenes, aryloxy ketenes and the simplest ketene) under different reaction conditions.[111–114]

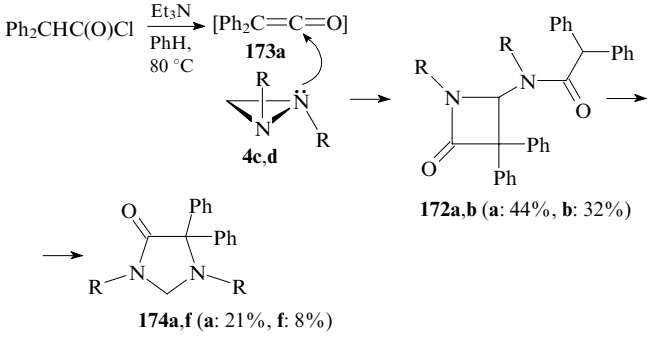
The reactions of 1,2-dialkyldiaziridines **4** with aryl ketenes **173** were first studied under mild conditions (at temperatures no higher than −30 °C). Aryl ketenes **173** were generated *in situ* from arylacetyl chlorides **139** in the presence of triethylamine in dry diethyl ether at −30 °C. Under these conditions, the reaction pathway differed from that described in the study[104] and the reaction produced 5-aryl-1,3-dialkylimidazolidin-4-ones **174a–e** in 40%–65% yields regardless of the acid chloride to diaziridine molar ratio, which was varied from 1:2 to 2:1. Evidently, this reaction proceeds through the formation of zwitterionic intermediates **175** followed by the N—N bond cleavage in the latter with the simultaneous attack of the carbanion on



Compound **174**	R^1	R^2	Ar	Compound **174**	R^1	R^2	Ar
a	Et	Ph	Ph	**d**	Et	H	2-$O_2NC_6H_4$
b	Et	H	4-MeC_6H_4	**e**	Pr^n	H	4-BrC_6H_4
c	Et	H	4-ClC_6H_4				

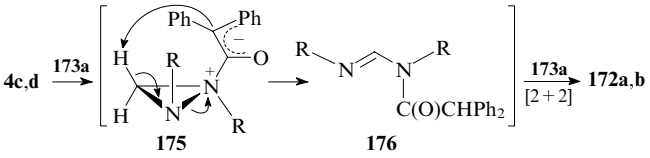
the second nitrogen atom to form 1,3-dialkylimidazolidin-4-ones **174**. It should be noted that this reaction provides a new route to compounds **174** by contrast to the known methods for the synthesis of the latter compounds, which are based on multistep processes. Racemic representatives of 5-aryl-1,3-dialkylimidazolidin-4-ones **174b–e** were separated into enantiomers by enantioselective gas chromatography.

With the aim of preparing new representatives of β-lactams, the reaction of 1,2-dialkyldiaziridines with diphenyl ketene (**173a**) was studied in more detail at high temperatures.[113] β-Lactams **172a,b** were isolated as the major products. However, in addition to β-lactams **172**, 1,3-dialkyl-5,5-diphenylimidazolidin-4-ones **174a,f** were obtained in low yields. The formation of the latter also proceeds *via* the diaziridine ring opening at the N—N bond.



R = Et (**4d**, **172a**, **174a**), Pr^n (**4c**, **172b**, **174f**).

Evidently, the mechanism of the transformation of 1,2-dialkyldiaziridines **4** into β-lactams **172** involves the formation of the above-mentioned zwitterionic intermediate **175** as the first step. Then the carbanion abstracts a proton from the C(3) atom of the diaziridine ring accompanied by the N—N bond cleavage and the formation of the new intermediate of the amidine type **176**. This intermediate is involved in the [2+2]-cycloaddition to the CH=N group of the second diphenyl ketene molecule to give β-lactams **172**. At low temperatures, the proton abstraction from the carbon atom of the diaziridine ring in zwitterion **175** apparently does not occur and the reaction produces imidazolidinones **174**.



Attempts to synthesize other β-lactams under the above-described conditions failed due, apparently, to the tendency of β-lactams bearing at least one hydrogen atom at position 3 to be cleaved to give dipolar intermediates stabilized as linear products. The structure of the latter is determined by the character of substituents at the other atoms of the four-membered ring. Evidently, the resulting β-lactams **172c–e** are cleaved to form new intermediates **177**, which are stabilized as linear *trans*-3,5-diazahept-1-enes **178a–c** (Scheme 14).

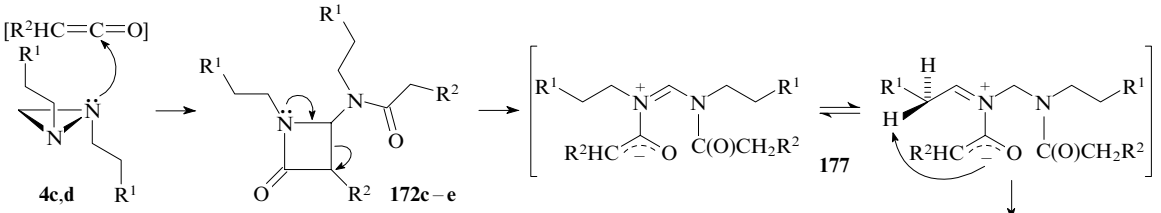
The reactions of 1,2-dialkyldiaziridines **4** with the simplest ketene were carried out at low temperatures because the latter is prone to dimerization. Unsubstituted ketene was generated *in situ* by the dropwise addition of acetyl chloride to a mixture of Et_3N and the starting diaziridine in dry diethyl ether at -40 °C. In this case, 3,5-diacetyl-3,5-diazahept-1-enes **178d–f** were also obtained as the major reaction products.

The proposed mechanism of the formation of compounds **178d–f** is similar to that described above. As in the above-considered cases, the first step of the reaction affords zwitterionic intermediates **175**. Then, as expected, the conjugated anion of intermediate **175** causes the abstraction of one of the hydrogen atoms bound to the carbon atom of the diaziridine ring, resulting in the N–N bond cleavage and the formation of intermediate *N*-acetylamidines **176**. In the next step, the [2 + 2]-cycloaddition of the second ketene molecule at the double bond of *N*-acetylamidines **176** gives β-lactams **172**, which are stabilized as linear structures (3,5-diacetyl-3,5-diazahept-1-enes **178d–f**) *via* the azetidine ring opening (Scheme 15).

To gain a deeper insight into the pathways of the reactions of diaziridines with ketenes, the mechanism of the reaction of the simplest representative of 1,2-disubstituted diaziridines (1,2-dimethyldiaziridine, **4e**) with unsubstituted ketene and phenyl ketene was studied by quantum chemical methods. The geometry optimization and the calculation of the energies of the transition and final states were performed with the use of the hybrid potential B3LYP and the standard 6–31G* basis set. The character of the stationary points was controlled by calculating the eigenvalues of the energy second-derivative matrix (the absence of imaginary frequencies for intermediates and one imaginary frequency for transition states). All calculations were performed with the use of the Gaussian 98 program package. The molecular structures and vibrations were visualized with the use of the MOLDEN graphics package.[114] According to the results of calculations, zwitterionic intermediate **175** is unstable and can dissociate into the starting compounds. The localization of transition state sructures **175a** corresponding to the proton migration from the C(3) atom to the CH_2 group (Fig. 1) was performed by calculations with full geometry optimization at the B3LYP/6-31* level of theory. The reaction produces amidine **176a**. The calculated activation energy for the reaction **4e** → **175a** → **176a** is $\Delta E^{\neq} = 20$ kcal mol^{-1}, and the energy gain upon the formation of amidine **176a** is $\Delta E = -79.4$ kcal mol^{-1}. The reaction exothermicity provides the necessary driving force for the reaction.

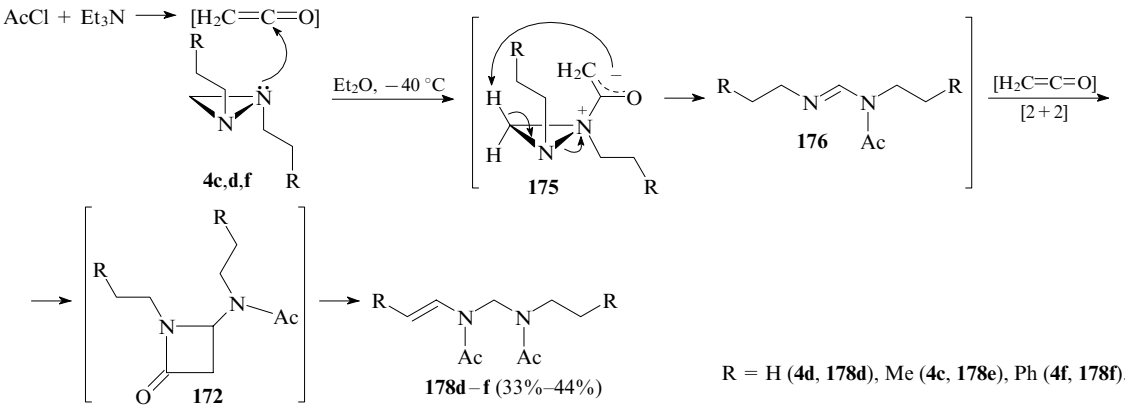
An attempt to calculate the corresponding transition state for phenyl ketene failed. Due to the steric effect of the phenyl group, the carbon atoms of the PhCH═ and CH_2

Scheme 14



Compound **172**	Compound **178**	R^1	R^2
c	**a**	H	4-ClC_6H_4O
d	**b**	H	4-BrC_6H_4
e	**c**	Me	4-ClC_6H_4

Scheme 15



R = H (**4d**, **178d**), Me (**4c**, **178e**), Ph (**4f**, **178f**).

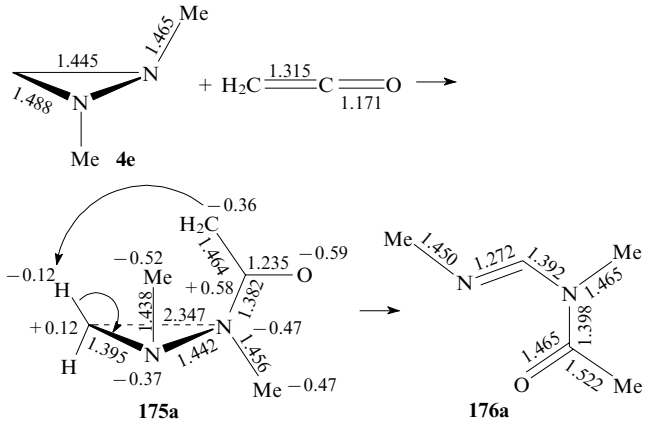


Figure 1. The calculated bond lengths (in Å) and charges for the reaction of *N*,*N*-dimethyldiaziridine with unsubstituted ketene.

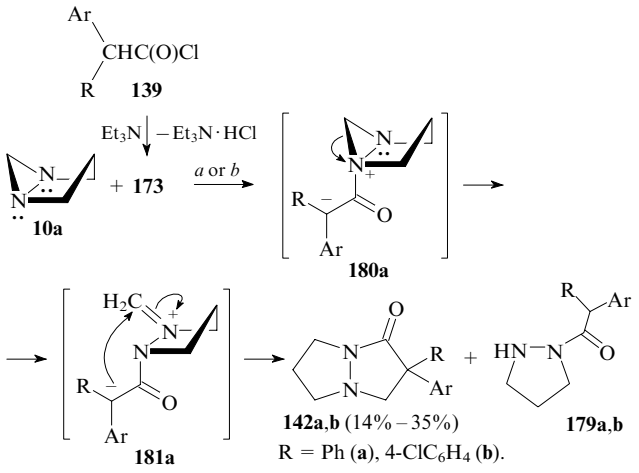
groups cannot approach each other to a distance necessary for proton migration.

b. Reactions of 1,5-diazabicyclo[3.1.0]hexanes with ketenes

As mentioned in the Introduction, the distinguishing structural feature of 1,5-diazabicyclo[3.1.0]hexanes **10** is that the nitrogen lone pairs of the diaziridine ring are in the *cis* orientation. Hence, their behaviour in the reaction with ketenes **173** has specific features. The reaction of equimolar amounts of 1,5-diazabicyclo[3.1.0]hexanes **10a**,**c**,**h** with monoaryl ketenes **173** was studied both at −30 °C in diethyl ether and at room temperature in benzene. In both cases, monocyclic products (1-acylpyrazolidines) **179** were isolated in 20%–48% yields as the reaction products, the yields in the reactions with 6-alkyl-substituted 1,5-diazabicyclo[3.1.0]hexanes **10c**,**h** being higher (45%–48%) (Scheme 16).[115]

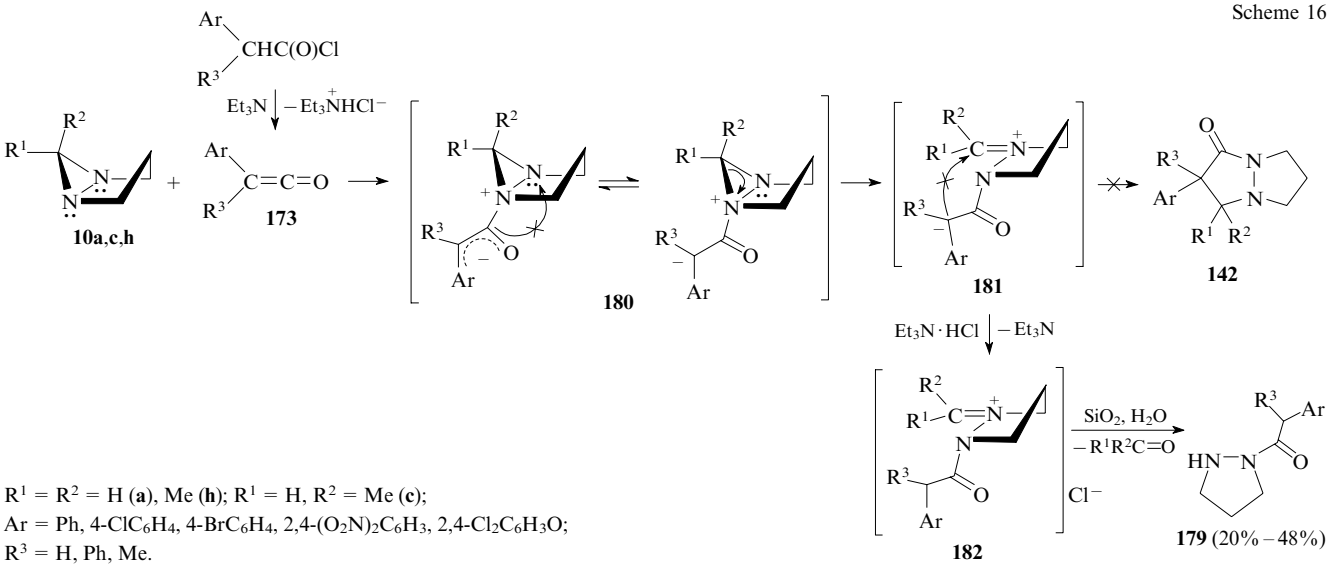
According to the mechanism proposed[115] for the reaction of 1,5-diazabicyclo[3.1.0]hexanes **10** with aryl ketenes, zwitterionic intermediates **180** are formed in the first step, as in the reaction with 1,2-dialkyldiaziridines **4**. However, since the nitrogen lone pairs in the starting compounds **10** are *cis*-oriented, the enolate ion in intermediates **180** cannot attack the second nitrogen atom accompanied by the N–N bond cleavage to form bicyclic compounds **142**. Hence, in this case the C–N bond cleavage occurs to form second intermediate **181**. The enolate ion in the latter behaves as a quite strong base and can abstract the HCl molecule from $Et_3N \cdot HCl$ (released into the medium upon the generation of ketenes) to give salts **182**, which are analogues of α-haloalkylamines. The latter are hydrolyzed to 1-acylpyrazolidines **179** and carbonyl compounds when contacting with water under the conditions of isolation. The cyclization of intermediate **181** to bicyclic system **142** (the *endo-trig* reaction) is, in principle, forbidden by the Baldwin rules because the attack of the nucleophilic enolate ion should occur either from above or below the $R^1R^2C{=}N$ plane, which is hardly probable from the point of view of the topology of the attack in intermediates **181** (Scheme 16).

However, under the thermodynamically controlled conditions and in the absence of substituents at position 6 of the starting bicyclic compound, there are two examples of the synthesis of compounds **142a**,**b**. In both cases, the corresponding 1-acylpyrazolidines **179a**,**b** were isolated as well. The formation of bicyclic compounds **142** can be



(*a*) for R = Ar = Ph (**142a**, **179a**); PhH, 20 °C;
(*b*) for R = H, Ar = 4-ClC_6H_4 (**142b**, **179b**); PhMe, 60–110 °C.

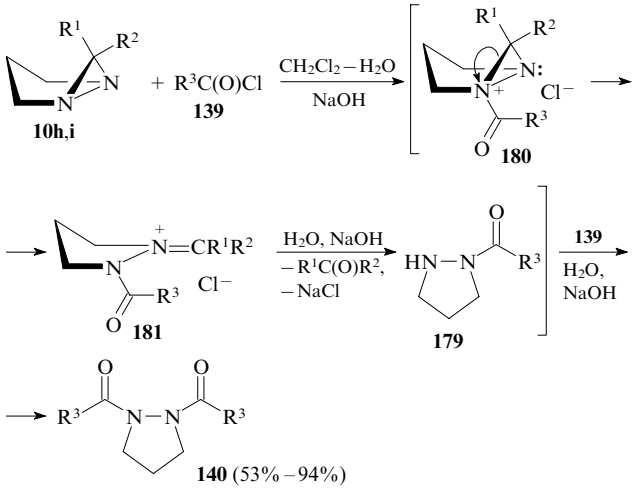
Scheme 16



$R^1 = R^2 = H$ (**a**), Me (**h**); $R^1 = H$, $R^2 = Me$ (**c**);
Ar = Ph, 4-ClC_6H_4, 4-BrC_6H_4, 2,4-$(O_2N)_2C_6H_3$, 2,4-$Cl_2C_6H_3O$;
R^3 = H, Ph, Me.

represented as a result of the intramolecular attack of the carbanion in intermediate **180a** on the C(6) atom of the 1,5-diazabicyclo[3.1.0]hexane system with the simultaneous C—N bond cleavage followed by the intramolecular attack of the carbanion in intermediate **181a** on the carbon atom of the iminium cation.

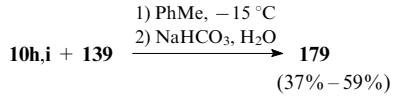
The proposed mechanism of the reaction producing compounds **179** can be formally considered as a sequence of acylation and hydrolysis steps. Based on the proposed mechanism, the authors modified the reaction by removing the carbanion in intermediates **180** and **181** due to the use of acyl chlorides **139** instead of ketenes as the acylating agents. The reaction of 1,5-diazabicyclo[3.1.0]hexanes **10h**,**i** with two equivalents of arylacetyl and aroyl chlorides **139** in the two-phase chloroform–(water + KOH) (NaOH or K_2CO_3) system produced 1,2-diacylpyrazolidines **140** in 53%–94% yields.



10h,**i** + R^{3}C(O)Cl (**139**) → (CH_2Cl_2–H_2O, NaOH) → **180** → **181** → (H_2O, NaOH; $-R^1C(O)R^2$, $-NaCl$) → **179** → (**139**, H_2O, NaOH) → **140** (53%–94%)

$R^1 = R^2 = Me$ (**h**); $R^1 = Pr^i$, $R^2 = H$ (**i**);
R^3 = 4-$ClC_6H_4CH_2$, 4-$BrC_6H_4CH_2$, 4-$FC_6H_4CH_2$, 4-ClC_6H_4, 2,4-$(O_2N)_2C_6H_3CH_2$, Bn, Ph, 2-Cl-6-$FC_6H_3CH_2$, 4-$ClC_6H_4OCMe_2$, 4-$MeOC_6H_4$, 4-$O_2NC_6H_4$.

For the selective synthesis of *N*-monoacylpyrazolidines **179**, it is preferable to perform the reaction at −15 °C in toluene with a twofold excess of the starting diaziridine.[95]

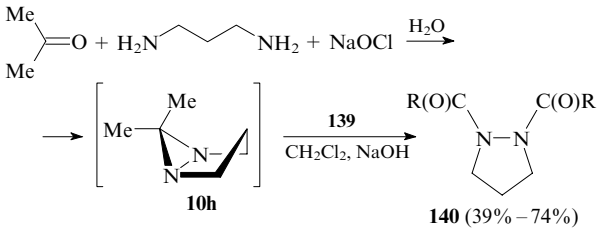


10h,**i** + **139** → (1) PhMe, −15 °C; (2) $NaHCO_3$, H_2O) → **179** (37%–59%)

R^3 = 4-$ClC_6H_4CH_2$, 4-$BrC_6H_4CH_2$, 4-$FC_6H_4CH_2$, 2,4-$(O_2N)_2C_6H_3CH_2$, 4-ClC_6H_4, 4-$ClC_6H_4OCMe_2$, 4-$O_2NC_6H_4$.

1-Acylpyrazolidines **179** are used as intermediates in the synthesis of important biologically active compounds (in particular, of new tumour necrosis factor inhibitors). The above-considered quite simple two-step method for the synthesis of compounds **179** (the synthesis of the starting bicyclic compounds **10** and their reactions with acyl chlorides) is a good supplement to the known methods.

An even more simple one-pot method for the synthesis of compounds **140** was developed in the study.[96] This method involves the synthesis of the starting 1,5-diazabicyclo[3.1.0]hexane **10h** from 1,3-diaminopropane, acetone and sodium hypochlorite in the chloroform–water system followed by the addition of an inorganic base and acyl chloride **139** without isolation of compounds **179**. In this case, the yields of pyrazolidines **140a**,**d** were 39%–74%.



Me$_2$C=O + $H_2N(CH_2)_3NH_2$ + NaOCl (H_2O) → **10h** → (**139**, CH_2Cl_2, NaOH) → **140** (39%–74%)

R = 2-Cl-6-FC_6H_3, 4-$MeOC_6H_4$, 4-$ClC_6H_4OCMe_2$.

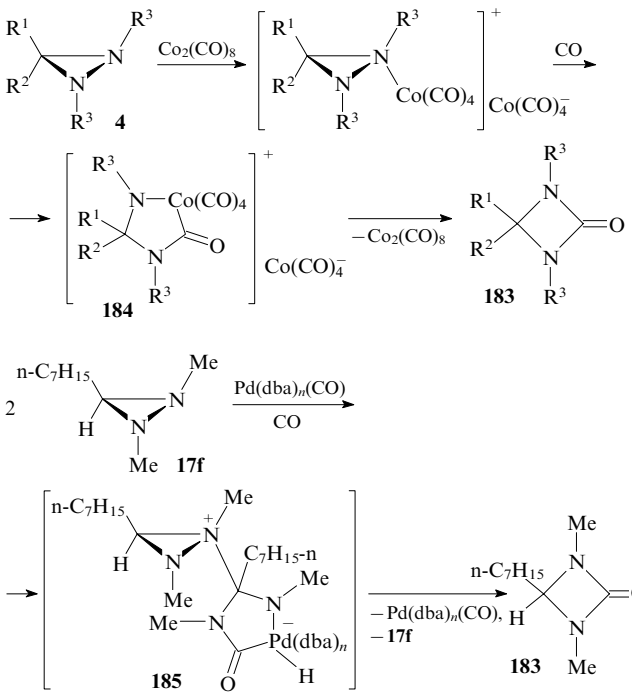
IX. Reactions of diaziridines with transition metal salts

The reactions of diaziridines with transition metal salts, which also belong to Lewis acids, can give either products of the transformation of the diaziridine ring or stable complexes.

1. Reactions of diaziridines through the intermediate complex formation

The complex formation of monocyclic diaziridines was suggested for the first time in studies of their chemical transformations in the presence of $Co_2(CO)_8$ as the catalyst (see the transformations of triaroyldiaziridines **119** synthesized from diaziridine **5g** in Section VII.1).[79]

More recently, $Co_2(CO)_8$ and $Pd(dba)_n(CO)$ (dba is dibenzylideneacetone) were used as the catalysts in the synthesis of aza-β-lactams **183** by the carbonylation of 1,2-dialkyldiaziridines **4** and **17**.[116] It was hypothesized that metal complexes with diaziridines **184** and **185** are formed as intermediates in these reactions.



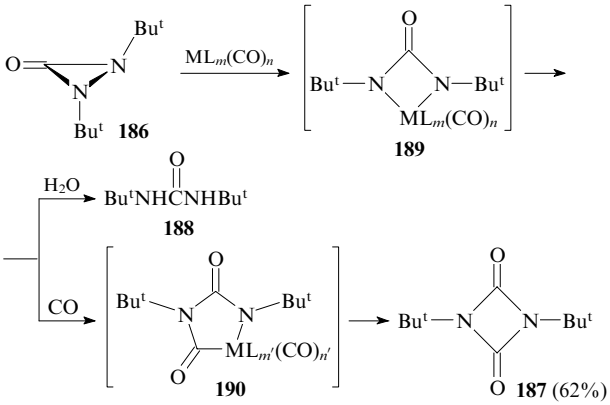
4 → ($Co_2(CO)_8$) → ($Co(CO)_4^-$, CO) → **184** → ($-Co_2(CO)_8$) → **183**

2 **17f** → ($Pd(dba)_n(CO)$, CO) → **185** → ($-Pd(dba)_n(CO)$, **−17f**) → **183**

A key effect of the complex formation on the diaziridine ring expansion was studied by the research group headed by Komatsu [117] for the carbonylation of 1,2-di(*tert*-butyl)diaziridin-2-one (**186**) in the presence of $Ni(CO)_4$ giving diazetidinedione **187** in 62% yield. The reaction was performed under an atmosphere of CO in DMF at 50 °C. Di(*tert*-butyl)urea (**188**) was obtained as a by-product. The reaction

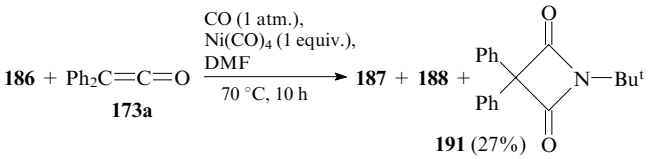
in the presence of $Pd(PPh_3)_4$ gave a similar result. The possible mechanism of this transformation is shown in Scheme 17. The first step leads to the oxidative addition of diaziridine to metal accompanied by the ring opening at the N–N bond and the formation of complex **189**. Then a CO molecule is inserted into **189** to form new complex **190** followed by the reductive elimination to give diazetidinedione **187**.

Scheme 17

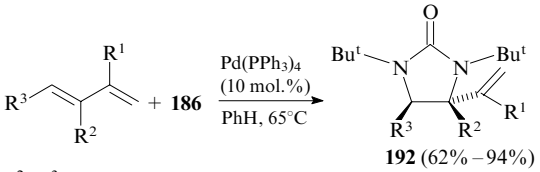


$ML_m(CO)_n$ = $Ni(CO)_4$ or $Pd(PPh_3)_3CO$ ($Pd(PPh_3)_4 \xrightarrow{CO} Pd(PPh_3)_3CO$).

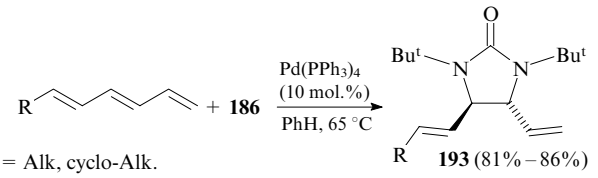
The corresponding reaction in the presence of diphenyl ketene affords azetidinedione **191** along with compounds **187** and **188**.



Recently, the research group headed by Yian Shi [118–129] performed studies on the catalytic regio-, stereo- and enantioselective diamination reactions of unsaturated compounds and active methylene groups under conditions of metal complex catalysis based on the diaziridine ring expansion in 1,2-di(*tert*-butyl)diaziridin-2-one (**186**). The first studies concerned with the Pd^0-catalyzed regio- and stereoselective diamination of conjugated dienes and trienes with the use of $Pd(PPh_3)_4$ as the catalysts. The reactions were performed in benzene at 60–65 °C under an argon flow for 0.5–5 h depending on the nature of the substituent in the substrate. The diamination of the conjugated dienes is a regioselective process that proceeds at the internal double bond (in the case of trienes, at the central double bond), only one stereoisomer of substituted imidazolidin-2-one **192** being formed (for trienes **193**).[118]



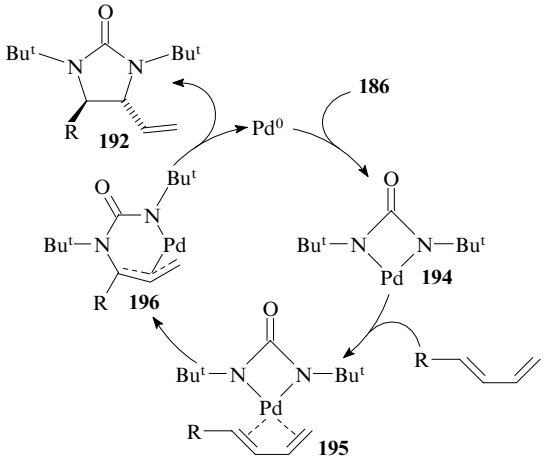
R^1, R^2, R^3 = Alk, Ar, Het, OAlk, CO_2Me.



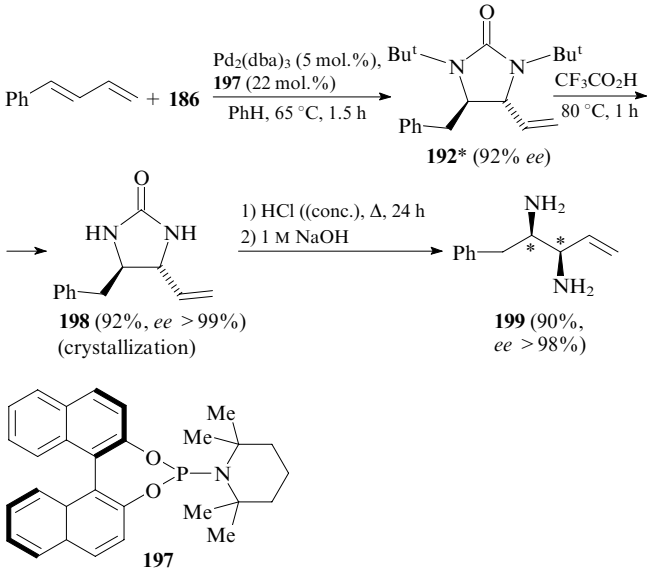
R = Alk, cyclo-Alk.

The catalytic cycle begins with the insertion of Pd^0 at the N–N bond of diaziridinone **186** to give four-membered intermediate **194**, which forms a complex with diene **195**. The latter is transformed into (π-allyl)-Pd complex **196** followed by the reductive elimination to form the final product **192** with regeneration of the Pd^0 catalyst (Scheme 18).

Scheme 18

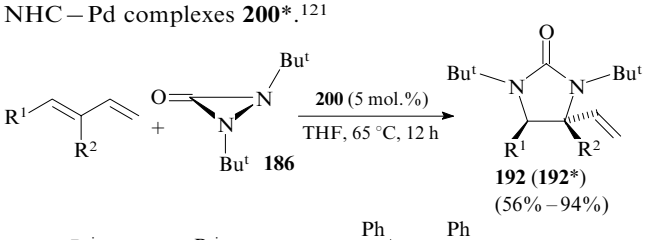


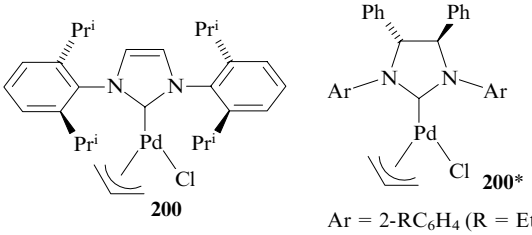
Under the same conditions, the asymmetric synthesis of imidazolidinones **192*** with the use of $Pd_2(dba)_3$ as the catalyst in the presence of chiral ligand **197** proceeds with high regio-, stereo- and enantioselectivity [(87%–95%) *ee*]. The treatment of compounds **192** with trifluoroacetic acid at 80 °C enables the *tert*-butyl deprotection of the nitrogen atoms. The hydrolysis of the resulting compounds **198** by concentrated HCl followed by the treatment with an aqueous alkali solution afforded optically active vicinal diamines **199** (an example with R = Ph was reported),[119] whose



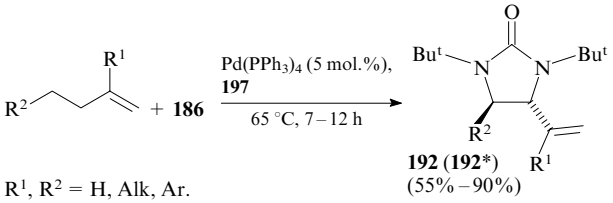
representatives are involved in many natural compounds and are important structural block in the asymmetric synthesis.

The catalytic diamination of conjugated dienes and trienes by 1,2-di(*tert*-butyl)diaziridin-2-one (**186**) was further developed by using Pd^0 complexes with N-heterocyclic carbenes (NHC–Pd) as the catalysts. Complex **200** with the addition of $NaOAm^t$ (Am^t is *tert*-pentyl) as the activator proved to be the most efficient catalyst in these reactions.[120] The reaction also proceeds with high regio- and stereoselectivity in high yields, and it was performed in the asymmetric version with (73%–76%) *ee* using chiral NHC–Pd complexes **200***.[121]





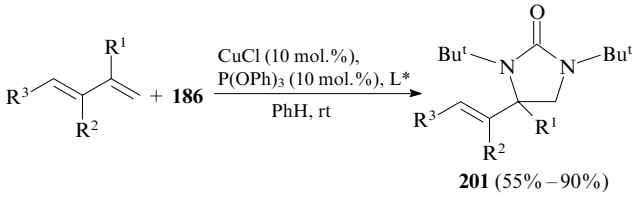
It was found that the reaction has a quite general character. The Pd^0 catalysts proved to be efficient in the diamination of terminal alkenes at the allylic and homoallylic carbon atoms *via* formal C–H activation. The reactions of terminal alkenes and diaziridinone **186** were performed without a solvent in the presence of $Pd(PPh_3)_4$ as the catalyst at 65 °C.[122] This reaction was carried out in the asymmetric version in the presence of chiral ligand **197** with high enantioselectivity [(90%–97%) *ee*].[123] The characteristic features of the synthesis and the mechanism of diamination of conjugated dienes with the use of diaziridinone **186** in the presence of Pd catalysts were discussed in the review.[124]



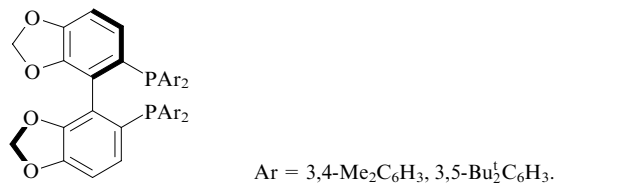
R1, R2 = H, Alk, Ar.

The use of Cu^I catalysts in this reaction instead of Pd complexes also proved to be efficient. The reaction proceeds with high regioselectivity under mild conditions; however, the diamination occurs at the terminal double to form imidazolidin-2-one **201**. In this case, CuCl in the presence of $P(OPh)_3$ was used as the catalyst.[125]

The Cu^I-catalyzed asymmetric diamination of various conjugated dienes and trienes was performed in the presence of Cu^I catalysts and the chiral biphosphine ligand (*R*)-DTBM-SEGPHOS [(23%–74%) *ee*].[126] The Cu^I-catalyzed reactions generally follow a radical mechanism. Possible mechanisms of the diamination of conjugated dienes were discussed in the study.[127]

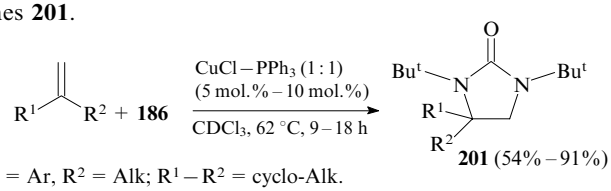


L* = (*R*)-DTBM-SEGPHOS, rt is room temperature.



(*R*)-DTBM-SEGPHOS

The Cu^I-catalyzed diamination of disubstituted terminal alkenes[128] and the Cu^I-catalyzed C–H-α amination of esters[129] and aryl ketones[130] are documented. The reactions of terminal alkenes with different types of substitution with 1,2-di(*tert*-butyl)diaziridin-2-one (**186**) were carried out in the presence of the CuCl–PPh_3 catalyst. The reactions proceeded in high yields under mild conditions (refluxing in chloroform) to form 4,4-disubstituted imidazolidin-2-ones **201**.

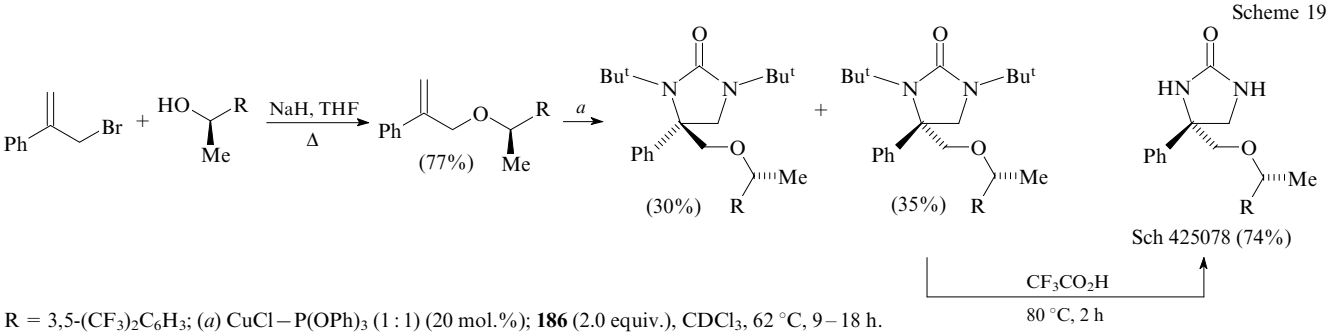


R1 = Ar, R2 = Alk; R1–R2 = cyclo-Alk.

The diamination reaction was used as the approach to the synthesis of the neurokinin receptor antagonist Sch 425078 (Scheme 19).[128]

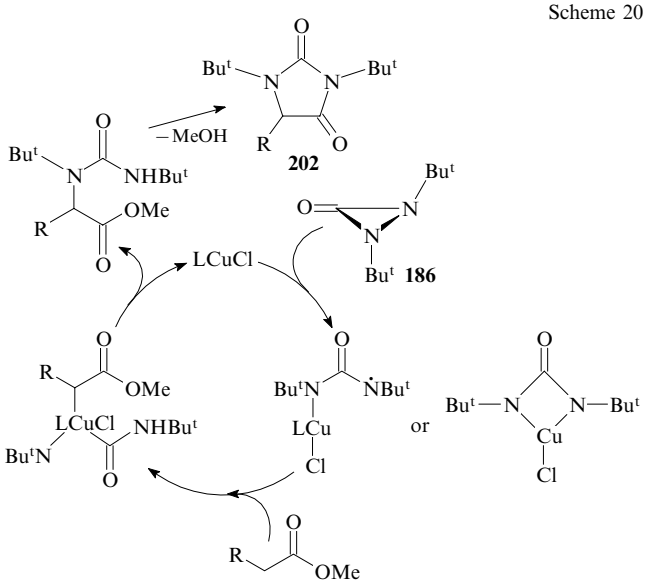
The Cu^I-catalyzed C–H-α amination of esters[129] and aryl ketones[130] with the use of 1,2-di(*tert*-butyl)diaziridin-

Scheme 19

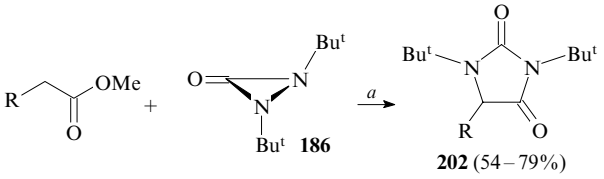


R = 3,5-$(CF_3)_2C_6H_3$; (*a*) CuCl–$P(OPh)_3$ (1 : 1) (20 mol.%); **186** (2.0 equiv.), $CDCl_3$, 62 °C, 9–18 h.

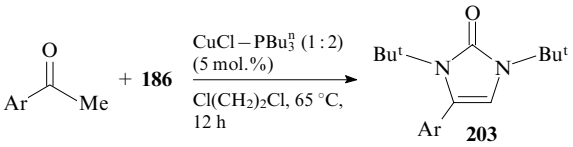
Scheme 20



2-one (**186**) as a source of nitrogen was performed in the presence of $CuCl-PBu^n_3$ as the catalyst under reflux in chloroform. In the former case, the reaction produced hydantoins **202**; in the latter case, imidazolidin-2-ones **203** were obtained in good yields. As mentioned above, the Cu^I-catalyzed reactions follow a radical mechanism.



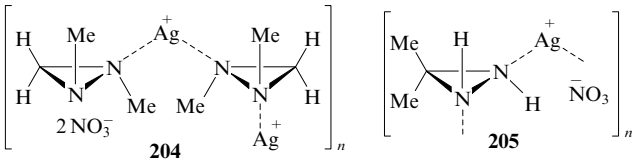
R = Alk, Ar, Het; (*a*) $CuCl-PBu^n_3$ (1 : 1) (5 mol.%), $CHCl_3$, 61 °C, 12 h.



Scheme 20 shows the possible catalytic cycle of the reaction giving hydantoins from esters.

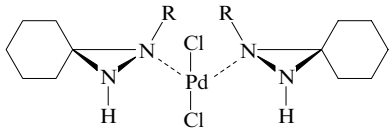
2. Stable complexes of diaziridines

Complexes of diaziridines with $AgNO_3$ were used in the study [131] for the spontaneous separation of enantiomers. The authors succeeded in synthesizing complexes **204** and **205** based on $AgNO_3$ and 1,2-dimethyldiaziridine (**4e**) and its isomer, 3,3-dimethyldiaziridine (**5a**).

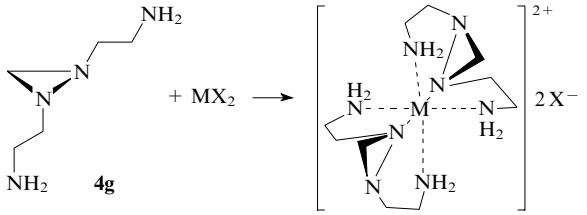


The spontaneous separation of enantiomers was performed for 3,3-dimethyldiaziridine (**5a**). It was shown that crystals of complex **205** consist of homochiral polymers. 3,3-Dimethyldiaziridine (**5a**) is the bidentate ligand; however, due to the *trans* orientation of the hydrogen atoms at the nitrogen atoms, the coordination of the latter to the metal cation occurs through polymerization. The molecular and crystal structure of complex **205** was established by X-ray diffraction. According to these data, both nitrogen atoms of the ring have the absolute *S,S* configuration. In the case of complex **204**, only the heterochiral polymer was isolated.

Complexes of *N*-alkyl-3,3-pentamethylenediaziridines with palladium chloride **206** were synthesized.[132] The diaziridine is coordinated to Pd by the more basic nitrogen atom bound to the alkyl substituent. The structures of the complexes were determined by X-ray diffraction. The coordination compounds have a square-planar structure (the diaziridine molecules occupy the diagonal vertices) and were obtained as mixtures of diastereomers. However, attempts to separate the diastereomers failed.

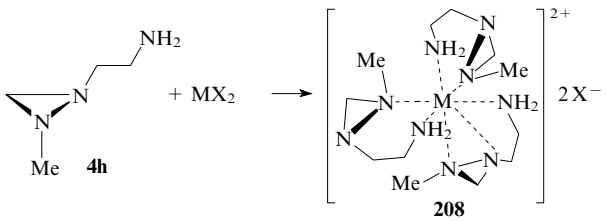


The complex formation of 1,2-bis(2-aminoethyl)diaziridine (**4g**) with Ni^{II}, Cd^{II}, Zn^{II}, Mn^{II} and Co^{II} salts was studied in detail.[133, 134] It was found that complexes **207** have the general formula $[M(L)_2]^{2+}X^-_2$. The structure of bis[1,2-bis(2-aminoethyl)diaziridine]cadmium perchlorate was confirmed by X-ray diffraction. According to the X-ray diffraction data, the Cd^{2+} ion in this complex is bound to two nitrogen atoms of the NH_2 groups and one nitrogen atom of each of two diaziridine molecules **4g**.



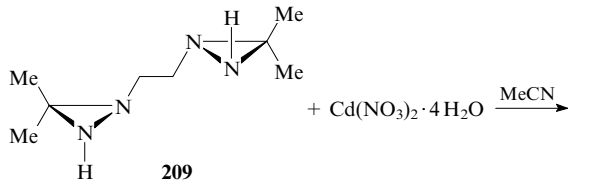
M = Zn, Cd, Ni, Co, Mn; X = NO_3, ClO_4.

Along with complexes **207**, a series of coordination compounds of 1-(2-aminoethyl)-2-methyldiaziridine (**4h**) with Zn^{II}, Cd^{II}, Ni^{II}, Co^{II}, Mn^{II} and Fe^{II} salts were synthesized.[134] The structures of these compounds were determined by IR and NMR spectroscopy. In this case, complexes **208** with the general formula $[M(L)_3]^{2+}X^-_2$ were obtained.



M = Zn, Cd, Ni, Co, Mn, Fe; X = NO_3, ClO_4.

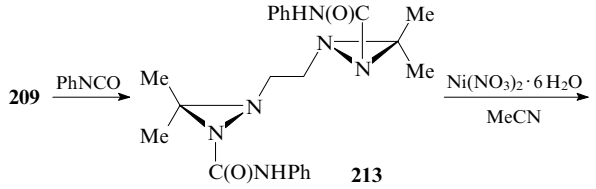
The synthesis of the first representative of cadmium complexes with 1,2-bis(3,3-dimethyldiaziridin-1-yl)ethane (**209**) was documented.[135] Complexes **210** and **211** were characterized by spectroscopic methods and X-ray diffraction.



L = **209**.

According to the X-ray diffraction data, the Cd^{2+} ion in compound **211** is coordinated by 1,2-bis(3,3-dimethyldiaziridin-1-yl)ethane (**209**) at the more basic nitrogen atoms of the ethylene-bridged diaziridine rings. Therefore, bis(diaziridine) **209** is a bidentate ligand. The methanol molecules and the nitrate ions are in the inner coordination sphere. In this compound, the coordination polyhedron of cadmium can be described as a distorted octahedron.

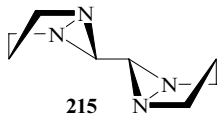
In the cited study, square-planar complex **212** of 1,2-bis(3,3-dimethyl-2-phenylcarbamoyldiaziridin-1-yl)ethane (**213**) with nickel nitrate was synthesized; the reaction of the latter complex with ammonium thiocyanate produced the octahedral complex $[Ni(L)(NCS)_2]$ (**214**).



L = **213**.

The structure of complex **214** was confirmed by X-ray diffraction. According to the X-ray diffraction data, the nitrate ions located in the outer coordination sphere of compound **212** are replaced by isothiocyanate ions, the latter being involved in the inner coordination sphere.

The complex formation of bicyclic diaziridine derivatives was studied[136] for 1,5-diazabicyclo[3.1.0]hexane derivatives, *viz*., 6-(4-methoxyphenyl)-1,5-diazabicyclo-[3.1.0]hexane (**10b**) and 6,6′-bis(1,5-diazabicyclo[3.1.0]hexane) (**215**). Studies by cyclic voltammetry showed that 1,5-diazabicyclo[3.1.0]hexanes can, in principle, form complexes with d metals. However, these compounds are much more sensitive to transition metal salts than monocyclic diaziridines. It was found that Co^{2+} and Ni^{2+} cations exert the same action on 1,5-diazabicyclo[3.1.0]hexanes as Lewis acids inducing the diaziridine ring opening at the C–N bond followed by its dimerization (in the case of Ni^{2+} salts) or polymerization (in the case of Co^{2+} salts).



Only complexes with Cd^{2+} salts proved to be stable. The reaction with bicyclic diaziridine **10b** (L_1) produced complexes of the composition $Cd(L_1)_4(OH)_2$ (in the synthesis with $Cd(ClO_4)_2$) and $Cd(L_1)_6(OH)_2$ (in the synthesis with $Cd(NO_3)_2$). The reactions with bis(diaziridine) **215** (L_2) gave complexes of the composition $Cd(L_2)(NO_3)_2$ and $Cd(L_2)_2(ClO_4)_2$. All products were characterized by ^1H NMR and IR spectroscopy and elemental analysis. The structure of the complex $Cd(L_2)(NO_3)_2$ was determined by X-ray diffraction. It was shown that this complex has the dimeric structure $Cd_2(L_2)_2(NO_3)_4$. Cadmium has the coordination number 8, and its polyhedron can be described as a square antiprism, all four nitrogen atoms of the starting bicyclic diaziridines being involved in the complex formation.

X. Conclusion

The data considered in the present review show that diaziridines can be widely used as building blocks for the synthesis of various nitrogen-containing heterocyclic structures and polyfunctional compounds of different types. In particular, the synthesis of hydrazines based on diaziridines has considerable advantages over the Raschig synthesis of hydrazines. The reactions of diaziridines with acylating agents performed in the first years after their discovery produced compounds, which can be easily transformed into various heterocyclic structures in the ring expansion reactions. In recent years, this field of chemical transformations of diaziridines with the use of electrophilic reagents has been most widely studied and yielded important practical results. In particular, simple methods were developed for the synthesis of bicyclic systems, close analogues of heterocyclic structures, which were covered by patents for the use in medicine, agriculture and other science and engineering fields (lubricants, semiconductors). Noteworthy are the reactions of 1,5-diazabicyclo[3.1.0]hexane derivatives proceeding *via* the generation of reactive azomethine imines, which are involved in 1,3-dipolar cycloaddition reactions with various dipolarophiles. A number of reactions of diaziridines were successfully performed with the use of ionic liquids as the reaction medium. In some cases, unpredictable diaziridine ring expansion reactions proceed to give six- and seven-membered nitrogen-containing heterocycles in one step. Due to the presence of nitrogen atoms in the diaziridine ring having a stable pyramidal configuration, a significant contribution was made to investigations of the stereochemistry of nitrogen and, in some cases, provided the stereoselectivity of the reactions with diaziridines. It is quite evident that the synthetic potential of readily available diaziridine derivatives as potential precursors in the route to practically important heterocyclic structures is far from being exhausted, as evidenced by a large number of publications in the last 10–15 years.

References

1. E Schmitz *Adv. Heterocycl. Chem.* **24** 63 (1979)
2. E Schmitz, in *Comprehensive Heterocyclic Chemistry* Vol. 7 (Ed. W Lwowski) (Oxford: Pergamon Press, 1984) p. 105
3. H W Heine, in *The Chemistry of Heterocyclic Compounds* Vol. 42 (Ed. A Hassner) (New York: Wiley-Interscience, 1983) p. 547
4. S M S Hai, A M Qureshi, A Bergan *Pakistan J. Sci. Ind. Res.* **18** 116 (1975)
5. R G Kostyanovsky, R Murugan, M Sitharchanavedi, in *Comprehensive Heterocyclic Chemistry II* Vol. 1A (Ed. A Padwa) (Oxford: Pergamon Press, 1996) p. 347
6. G D McAllister, A Perry, R J K Taylor, in *Comprehensive Heterocyclic Chemistry III* Vol. 1 (Ed. A Padwa) (New York: Elsevier, 2008) p. 539

7. E Shmits *Dreiring mit zwei Heteroatomen* (Berlin: Springer, 1967)
8. GB P. 890334 (1962); *Chem. Abstr.* **58** 1463a (1963)
9. R Ohme, E Schmitz, P Dolge *Chem. Ber.* **99** 2104 (1966)
10. NL P. 6411384 (1965); *Chem. Abstr.* **64** 3358d (1966)
11. E Schmitz *Angew. Chem.* **71** 127 (1959)
12. E Schmitz, R Ohme *Chem. Ber.* **95** 2012 (1962)
13. Yu B Koptelov, R R Kostikov, A P Molchanov, Yu Kopf *Zh. Org. Khim.* **35** 149 (1999) [a]
14. Yu B Koptelov *Zh. Org. Khim.* **42** 1524 (2006) [a]
15. R G Kostyanovsky, G V Shustov, N I Zaichenko *Tetrahedron* **38** 949 (1982)
16. R G Kostyanovsky, G V Shustov, O G Nabiev, S N Denisenko, S A Sukhanova, E F Lavretskaya *Khim.-Farm. Zh.* **20** 671 (1996) [b]
17. E Schmitz, D Habisch *Chem. Ber.* **95** 680 (1962)
18. G V Shustov, A Yu Shibaev, Yu V Puzanov, R G Kostyanovsky *Izv. Akad. Nauk SSSR, Ser. Khim.* 1869 (1988) [c]
19. B Carboni, L Toupet, R Carrié *Tetrahedron* **43** 2293 (1987)
20. S V Varlamov, G K Kadorkina, R G Kostyanovsky *Khim. Geterotsikl. Soedin.* 390 (1988) [d]
21. N N Makhova, G A Karpov, A N Mikhailyuk, L I Khmel'nitskii *Mendeleev Commun.* 112 (1999)
22. H Böhme, J-P Denis, T Kämpchen *Chem. Ber.* **115** 2947 (1982)
23. Yu B Koptelov, A P Molchanov, R R Kostikov *Zh. Org. Khim.* **36** 1056 (2000) [a]
24. USSR P. 469699 (1975); *Byull. Izobret.* (17) 66 (1975)
25. O G Nabiev, M A Shakhgel'diev, I I Chervin, R G Kostyanovsky *Dokl. Akad. Nauk SSSR* **284** 872 (1985) [e]
26. R G Kostyanovsky, K S Zakharov, M Zaripova, V F Rudchenko *Izv. Akad. Nauk SSSR, Ser. Khim.* 875 (1975) [c]
27. R G Kostyanovcky, G V Shustov, V I Markov *Izv. Akad. Nauk SSSR, Ser. Khim.* 2823 (1974) [c]
28. N N Makhova, A N Mikhailyuk, A E Bova, T V Chabina, L I Khmel'nitskii *Izv. Akad. Nauk, Ser. Khim.* 2091 (1993) [c]
29. G V Shustov, S N Denisenko, I I Chervin, R G Kostyanovsky *Izv. Akad. Nauk SSSR, Ser. Khim.* 2643 (1984) [c]
30. H W Heine, R Henrie II, L Heintz, S R Kovvali *J. Org. Chem.* **39** 3187 (1974)
31. A A Dudinskaya, A E Bova, L I Khmel'nitskii, S S Novikov *Izv. Akad. Nauk SSSR, Ser. Khim.* 1523 (1971) [c]
32. N N Makhova, A N Mikhailyuk, A E Bova, V Yu Petukhova, T V Chabina, L I Khmel'nitskii *Mendeleev Commun.* 146 (1992)
33. S N Denisenko, G V Shustov, I I Chervin, R G Kostyanovsky *Khim. Geterotsikl. Soedin.* 1348 (1985) [d]
34. A V Shevtsov, V Yu Petukhova, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 2160 (2003) [c]
35. A V Shevtsov, V Yu Petukhova, N N Makhova, K A Lysenko *Izv. Akad. Nauk, Ser. Khim.* 1381 (2002) [c]
36. G V Shustov, Doctoral Thesis in Chemical Sciences, Institute of Chemical Physics, Russian Academy of Sciences, Moscow, 1987
37. R G Kostyanovsky, G K Kadorkina, S V Varlamov, I I Chervin, I K A R Maldonado *Khim. Geterotsikl. Soedin.* 472 (1988) [d]
38. G V Shustov, S N Denisenko, M A Shokhen, R G Kostyanovsky *Izv. Akad. Nauk SSSR, Ser. Khim.* 1862 (1988) [c]
39. R G Kostyanovsky, A E Polyakov, V I Markov *Izv. Akad. Nauk SSSR, Ser. Khim.* 198 (1975) [c]
40. V A Korneev, G V Shustov, I I Chervin, R G Kostyanovsky *Izv. Akad. Nauk, Ser. Khim.* 1396 (1995) [c]
41. GB P. 1081292 (1967); *Chem. Abstr.* **68** 114071 (1968)
42. K Hori, H Sugihara, Y N Ito, T Katsuki *Tetrahedron Lett.* **40** 5207 (1999)
43. H Ishihara, K Hori, H Sugihara, Y N Ito, T Katsuki *Helv. Chim. Acta* **85** 4272 (2002)
44. H Ishihara, Y N Ito, T Katsuki *Chem. Lett.* **30** 984 (2001)
45. J W Lown *J. Chem. Soc. C* 1338 (1969)
46. E V Dehmlow, J Schonefeld *Z. Naturforsh., B: Anorg. Chem., Org. Chem.* **30** 824 (1975)
47. Yu B Koptelov, M Kh Kim, A P Molchanov, R R Kostikov *Zh. Org. Khim.* **35** 116 (1999) [a]
48. A P Molchanov, D I Sipkin, Yu B Koptelov, R R Kostikov *Zh. Org. Khim.* **37** 888 (2001) [a]
49. A P Molchanov, D I Sipkin, Yu B Koptelov, J Kopf, R R Kostikov *Zh. Org. Khim.* **39** 1410 (2003) [a]
50. A P Molchanov, D I Sipkin, Yu B Koptelov, R R Kostikov *Eur. J. Org. Chem.* 453 (2002)
51. A P Molchanov, D I Sipkin, Yu B Koptelov, J Kopf, R R Kostikov *Zh. Org. Khim.* **40** 76 (2004) [a]
52. Yu B Koptelov, A I Ukolov, in *Materialy Mezhdunarodnoi Konferentsii po Organicheskoi Khimii 'Organicheskaya Khimiya ot Butlerova i Beilshteina do Sovremennosti'* (Proceedings of International Conference on Organic Chemistry 'Organic Chemistry from Butlerov and Beilstein to the Present Time', St Petersburg, 2006) p. 600
53. Yu B Koptelov, S P Saik, in *Materialy Mezhdunarodnoi Konferentsii po Organicheskoi Khimii 'Organicheskaya Khimiya ot Butlerova i Beilshteina do Sovremennosti'* (Proceedings of International Conference on Organic Chemistry 'Organic Chemistry from Butlerov and Beilstein to the Present Time', St Petersburg, 2006) p. 601
54. Yu B Koptelov, S P Saik, A P Molchanov *Khim. Geterotsikl. Soedin.* 1071 (2008) [d]
55. S P Saik, Yu B Koptelov, A P Molchanov *Vestn. SPbGU, Ser. 4* 86 (2009)
56. Yu S Syroeshkina, V V Kachala, I V Ovchinnikov, V V Kuznetsov, Yu V Nelyubina, K A Lyssenko, N N Makhova *Mendeleev Commun.* **19** 276 (2009)
57. Yu S Syroeshkina, L L Fershtat, V V Kachala, V V Kuznetsov, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 1579 (2010) [c]
58. T Welton *Chem. Rev.* **99** 2071 (1999)
59. P Wasserscheid, W Keim *Angew. Chem., Int. Ed.* **39** 3772 (2000)
60. *Ionic Liquids in Synthesis* Vol. 1 (Eds P Wasserscheid, T Welton) (Weinheim: Wiley-VCH, 2008)
61. *Ionic Liquids in Synthesis* Vol. 2 (Eds P Wasserscheid, T Welton) (Weinheim: Wiley-VCH, 2008)
62. D L Astolfi, F C Mayville Jr *Tetrahedron Lett.* **44** 9223 (2003)
63. S G Zlotin, N N Makhova *Mendeleev Commun.* **20** 63 (2010)
64. S G Zlotin, N N Makhova *Russ. Chem. Rev.* **79** 543 (2010)
65. R G Kostyanovsky, Yu I El'natanov *Izv. Akad. Nauk SSSR, Ser. Khim.* 2581 (1983) [c]
66. Yu I El'natanov, R G Kostyanovsky *Izv. Akad. Nauk SSSR, Ser. Khim.* 1858 (1988) [c]
67. H W Heine, L S Lehman, A P Glaze, A W Douglas *J. Org. Chem.* **45** 1317 (1980)
68. T K Klindukhova, V N Yandovskii *Zh. Org. Khim.* **10** 877 (1974) [a]
69. Yu S Syroeshkina, V V Kuznetsov, V V Kachala, N N Makhova *J. Heterocycl. Chem.* **46** 1195 (2009)
70. V Yu Petukhova, L L Fershtat, V V Kachala, V V Kuznetsov, D V Khakimov, T S Pivina, N N Makhova *J. Heterocycl. Chem.* **49** (2012) (in the press)
71. Yu S Syroeshkina, V V Kuznetsov, M I Struchkova, M A Epishina, N N Makhova *Mendeleev Commun.* **18** 207 (2008)
72. Yu S Syroeshkina, V V Kuznetsov, K A Lysenko, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 362 (2009) [c]
73. E Schmitz, D Habisch, C Gründemann *Chem. Ber.* **100** 142 (1967)
74. E Schmitz, D Habisch *Rev. Chim. Acad. Rep. Populaire Roum.* **7** 1281 (1962)
75. E Schmitz, R Ohme, S Schramm *Tetrahedron Lett.* 1857 (1965)

76. DE P. 1136343 (1962); *Chem. Abstr.* **58** 3436g (1963)
77. L Somogyi *Chem. Ber.* **119** 2963 (1986)
78. S D Isaev, G G Zhalnina, Z N Murzinova, T V Ivzhenko, A G Yurchenko *Zh. Org. Khim.* **24** 2611 (1988)
79. D Roberto, H Alper *J. Chem. Soc., Chem. Commun.* 212 (1987)
80. S E Mangholz, K Briner, B Bernet, A Vasella *Helv. Chim. Acta* **86** 2490 (2003)
81. R G Kostianovsky, K S Zakharov, M Zaripova, V F Rudchenko *Tetrahedron Lett.* 4207 (1974)
82. G V Shustov, G K Kadorkina, S V Varlamov, A V Kachanov, R G Kostyanovsky, A Rauk *J. Am. Chem. Soc.* **114** 1616 (1992)
83. H W Heine, L M Baclawski, S M Bonser, G D Wachob *J. Org. Chem.* **41** 3229 (1976)
84. H W Heine, L Heitz *J. Org. Chem.* **39** 3192 (1974)
85. E S Gubnitskaya, V S Parkhomenko *Zh. Obshch. Khim.* **50** 1502 (1980) [f]
86. R G Kostyanovsky, A E Polyakov, G V Shustov, K S Zakharov, V I Markov *Dokl. Akad. Nauk SSSR* **219** 873 (1974) [e]
87. R G Kostyanovsky, A E Polyakov, V I Markov *Izv. Akad. Nauk SSSR, Ser. Khim.* 1671 (1974) [c]
88. R G Kostyanovsky, A E Polyakov, G V Shustov *Tetrahedron Lett.* 2059 (1976)
89. S V Konovalikhin, A B Zolotoi, L O Atovmyan, G V Shustov, S N Denisenko, R G Kostyanovsky *Izv. Akad. Nauk, Ser. Khim.* 500 (1995) [c]
90. SSSR P. 523092; *Byull. Izobret.* (28) 63 (1976)
91. JP P. 7005544 (1970); *Chem. Abstr.* **72** 111106 (1970)
92. Yu S Syroeshkina, V Yu Petukhova, V V Kachala, Yu V Nelyubina, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 1401 (2010) [c]
93. L S Lehman, L M Baclawski, S A Harris, H W Heine, J P Springer, W J A VandenHeuvel, B H Arison *J. Org. Chem.* **46** 320 (1981)
94. R G Kostyanovsky, G V Shustov, A I Mishchenko, V I Markov *Izv. Akad. Nauk SSSR, Ser. Khim.* 2026 (1976) [c]
95. A V Shevtsov, A A Kislukhin, V V Kuznetsov, V Yu Petukhova, V A Maslennikov, A O Borissova, K A Lyssenko, N N Makhova *Mendeleev Commun.* **17** 119 (2007)
96. V Yu Petukhova, V A Maslennikov, V V Kuznetsov, N N Makhova, S A Serkov *Izv. Akad. Nauk, Ser. Khim.* 1388 (2010) [c]
97. G Sosnovsky, J Lukszo *Z. Naturforsh., B: Anorg. Chem., Org. Chem.* **38** 884 (1983)
98. Yu S Syroeshkina, V V Kuznetsov, K A Lyssenko, N N Makhova *Mendeleev Commun.* **18** 42 (2008)
99. H J Abendroth *Angew. Chem.* **73** 67 (1961)
100. E Schmitz, C Hörig, C Gründemann *Chem. Ber.* **100** 2093 (1967)
101. G Zinner, K Dorschner *Arch. Pharm.* **306** 35 (1973)
102. A Nabeya, Y Tamura, T Kodama, Y Iwakura *J. Org. Chem.* **38** 3758 (1973)
103. A Nabeya, J Saito, H Koyama *J. Org. Chem.* **44** 3935 (1979)
104. M Komatsu, N Nishikaze, M Sakamoto, Y Oshihiro, T Agawa *J. Org. Chem.* **39** 3198 (1974)
105. G L'Abbé, C-C Yu, S Toppet *Angew. Chem.* **89** 492 (1977)
106. N N Makhova, V Yu Petukhova, T V Chabina, L I Khmel'nitskii *Izv. Akad. Nauk, Ser. Khim.* 1665 (1993) [c]
107. A V Shevtsov, V V Kuznetsov, S I Molotov, K A Lysenko, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 534 (2006) [c]
108. A V Shevtsov, V V Kuznetsov, K A Lyssenko, P A Belyakov, N N Makhova *Mendeleev Commun.* 218 (2006)
109. A P Molchanov, D I Sipkin, Yu B Koptelov, R R Kostikov *Synlett* 1779 (2000)
110. Yu B Koptelov, S P Saik *Zh. Org. Khim.* **42** 1515 (2006) [a]
111. A V Shevtsov, V Yu Petukhova, Yu A Strelenko, K A Lyssenko, I V Fedyanin, N N Makhova *Mendeleev Commun.* 221 (2003)
112. A V Shevtsov, V Yu Petukhova, Yu A Strelenko, N N Makhova *Mendeleev Commun.* 29 (2005)
113. A V Shevtsov, V Yu Petukhova, Yu A Strelenko, K A Lysenko, N N Makhova V A Tartakovskii *Izv. Akad. Nauk, Ser. Khim.* 997 (2005) [c]
114. A V Shevtsov, V P Ananikov, N N Makhova *Zh. Org. Khim.* **43** 1113 (2007) [a]
115. A V Shevtsov, V V Kuznetsov, A A Kislukhin, V Yu Petukhova, Yu A Strelenko, N N Makhova *J. Heterocycl. Chem.* **43** 881 (2006)
116. H Alper, D Delledonne, M Kameyama, D Roberto *Organometallics* **9** 762 (1990)
117. M Komatsu, S Tamabuchi, S Minakata, Y Ohshiro *Heterocycles* **50** 67 (1999)
118. H Du, B Zhao, Y Shi *J. Am. Chem. Soc.* **129** 762 (2007)
119. H Du, W Yuan, B Zhao, Y Shi *J. Am. Chem. Soc.* **129** 11688 (2007)
120. L Xu, H Du, Y Shi *J. Org. Chem.* **72** 7038 (2007)
121. L Xu, Y Shi *J. Org. Chem.* **73** 749 (2008)
122. H Du, W Yuan, B Zhao, Y Shi *J. Am. Chem. Soc.* **129** 7496 (2007)
123. H Du, B Zhao, Y Shi *J. Am. Chem. Soc.* **130** 8590 (2008)
124. B Zhao, H Du, S Cui, Y Shi *J. Am. Chem. Soc.* **132** 3523 (2010)
125. W Yuan, H Du, B Zhao, Y Shi *Org. Lett.* **9** 2589 (2007)
126. H Du, B Zhao, W Yuan, Y Shi *Org. Lett.* **10** 4231 (2008)
127. B Zhao, X Peng, S Cui, Y Shi *J. Am. Chem. Soc.* **132** 11009 (2010)
128. Y Wen, B Zhao, Y Shi *Org. Lett.* **11** 2365 (2009)
129. B Zhao, H Du, Y Shi *J. Am. Chem. Soc.* **130** 7220 (2008)
130. B Zhao, H Du, Y Shi *J. Org. Chem.* **74** 4411 (2009)
131. R G Kostyanovsky, Yu A El'Natanov, K A Lyssenko, M Yu Antipin, V R Kostyanovsky, in *The 6th International Conference on Circular Dichroism (Book of Abstracts), Piza, Italy, 1997* p. 98
132. P F S Filho, H O Pastore *J. Chem. Res., Synop.* 326 (1989)
133. V P Sinditskii, M D Dutov, A E Fogel'zang, V V Kuznetsov *Zh. Neorg. Khim.* **36** 944 (1991) [g]
134. A V Shevtsov, V Yu Petukhova, S A Kutepov, V V Kuznetsov, N N Makhova, N E Kuz'mina, G G Aleksandrov *Izv. Akad. Nauk, Ser. Khim.* 1910 (2000) [c]
135. T V Skrupskaya, A A Kislukhin, A V Shevtsov, V Yu Petukhova, K A Lysenko, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 53 (2008) [c]
136. Yu S Syroeshkina, L L Fershtat, M A Syroeshkin, V V Kuznetsov, K A Lysenko, N N Makhova *Izv. Akad. Nauk, Ser. Khim.* 977 (2009) [c]

[a] — *Russ. J. Org. Chem. (Engl. Transl.)*
[b] — *Pharm. Chem. J. (Engl. Transl.)*
[c] — *Russ. Chem. Bull., Int. Ed. (Engl. Transl.)*
[d] — *Chem. Heterocycl. Compd. (Engl. Transl.)*
[e] — *Dokl. Chem. (Engl. Transl.)*
[f] — *Russ. J. Gen. Chem. (Engl. Transl.)*
[g] — *Russ. J. Inorg. Chem. (Engl. Transl.)*