Four-membered rings from isocyanides: Developments since the mid 1980s

Dietrich Moderhack

Institute of Medicinal and Pharmaceutical Chemistry, Technical University of Braunschweig
D-38106 Braunschweig, Germany, Beethovenstraße 55
E-mail: d.moderhack@tu-bs.de

Dedicated to Professor Rosa M. Claramunt on the occasion of her 65th birthday

DOI: http://dx.doi.org/10.3998/ark.5550190.p008.224

Abstract

Reactions of isocyanides with open-chain and cyclic substrates leading to four-membered rings are reviewed. The survey is intended to be illustrative rather than encyclopedic.

Keywords: Isocyanides, cyclization, insertion, heterocycles, element-organic rings

---

Table of Contents

1. Introduction

Within the wide area of cyclizations involving the isocyano group the direct formation of four-membered rings constitutes an especially intriguing process because of elements of serendipity. The first discoveries date back to the 1960s and were summarized at the end of the decade.[1] The period till 1985, however, proved prolific to such an extent as to warrant a second review.[2] Since that time again new results have emerged in great number; this may justify the present survey.[3] Viewing the rich material, two features stand out: (i) The ring-forming principles have almost trebled so as to exclude an introductory graphic of the kind shown in ref.[2]; (ii) regarding the type of products, a plethora of element-organic rings have arisen.[4]

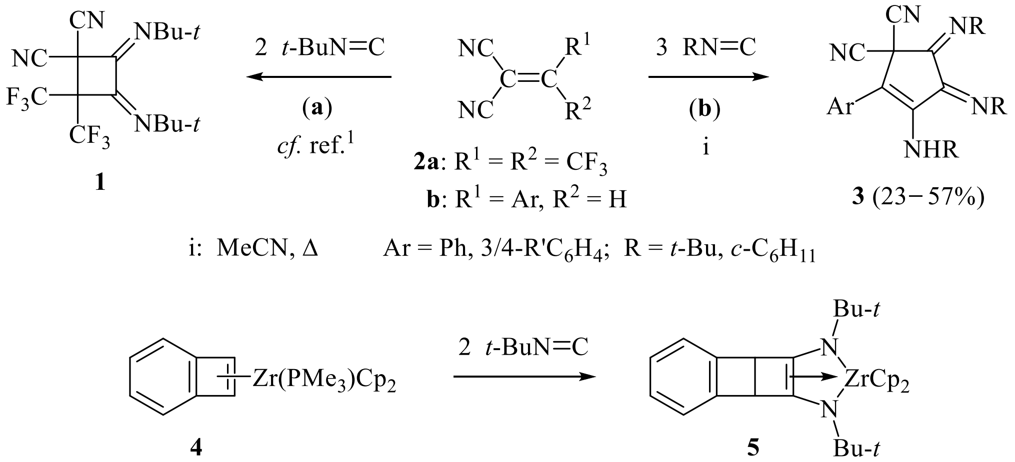
Adhering to style and format of the earlier review,[2] presentation of all new material will be arranged according to starting compounds rather than to products or actual mechanisms.

2. Reaction of isocyanides with open-chain substrates

2.1. [1+1+2] Cycloaddition of isocyanides to double and triple bond systems

Alkenes: While a methylenemalononitrile bearing two acceptor groups like the derivative **2a** reacts with *tert*-butyl isocyanide to produce the cyclobutanediimine **1** (Scheme 1),[1] benzylidene analogs (even though substituted with a nitro or fluoro group at the phenyl ligand) were shown to take up three molecules of the isocyanide to yield the five-membered ring **3** instead.[5]

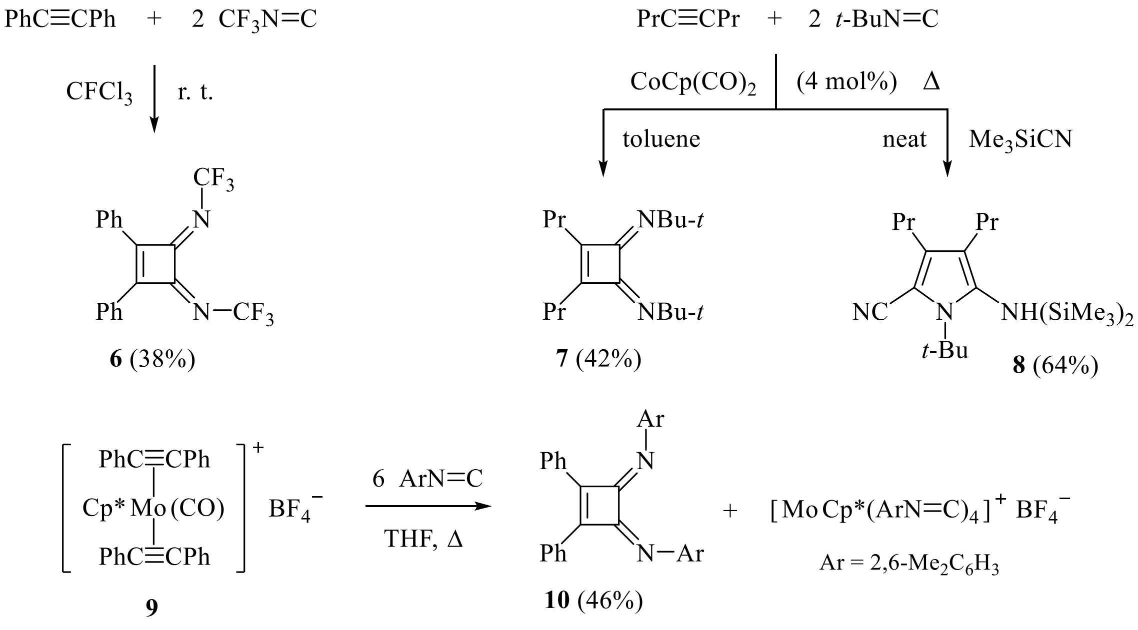
Though not being an open-chain substrate, the behavior of the benzocyclobutadiene complex **4** may be compared to that of **2a**. When two equivalents of *tert*-butyl isocyanide were added to **4**, the reagent underwent smooth insertion into both Zr–C bonds to eventually afford the Dewar-naphthalene **5**, the structure of which was established by X-ray diffraction.[6] Double insertion of *tert*-butyl isocyanide had been observed before also with the cyclobutene analog of **4**, but in that case the carbon atoms of the two isocyanides did not couple to give a four-membered ring.[7]



Scheme 1

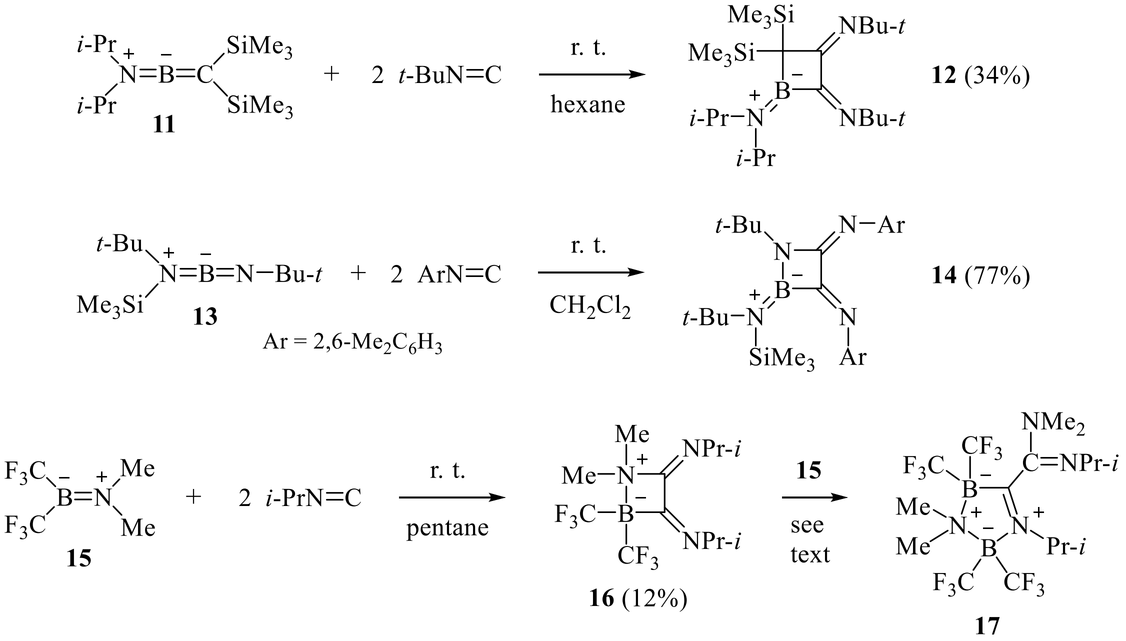
Alkynes: Open-chain representatives devoid of an acceptor or donor group are usually inert towards isocyanides. As an exception, a [1+1+2] cycloaddition took place very readily when diphenylethyne was treated with trifluoromethyl isocyanide to afford the cyclobutenediimine **6** (Scheme 2). The structure of this material was determined by an X-ray structure analysis, showing that the imino functions are *E* and *Z* configured. Traces of a (mono)ketone arise unless the solvent is rigorously dried.[8] Similar reactions of this isocyanide were reported – but without experimental details – for but-2-yne and ethoxyethyne, whereas hexafluorobutyne and fluoroalkenes were said to be inert.[9]

However, transition metal-induced [1+1+2] cycloadditions are relatively frequent (*cf.* ref.[2]); more recent examples include the following: (i) When oct-4-yne was heated with *tert*-butyl isocyanide and a catalytic amount of dicarbonylcyclopentadienylcobalt(I), the cyclobutenediimine **7** was obtained.[10] Yet, on adding – as a fourth component – trimethylsilyl cyanide (which equilibrates with the isocyanide *in situ*), the pyrrole **8** resulted (or its *N*-unsubstituted congener if *tert*-butyl isocyanide was replaced with cyclohexyl isocyanide). (ii) When the cationic molybdenum complex **9** was treated with six equivalents of 2,6-dimethylphenyl isocyanide, alkyne–isocyanide coupling gave rise to the four-membered ring **10**.[11] According to the X-ray analysis, the imino groups are configured as observed earlier with the product **6**.[8] – For a further example following the formal [1+1+2] cycloaddition pattern, *cf.* Section 3.2.



Scheme 2

Alkylidene-, imino-, aminoboranes: Compounds of the type **11** and **13** were shown to take up two isocyanide molecules very readily (Scheme 3). Treatment of the allene-type system **11** with *tert*-butyl isocyanide afforded the boretanediimine **12**, even when using less than two equivalents of the isocyanide.[12] Accordingly, action of 2,6-dimethylphenyl isocyanide on the iminoborane **13** led to the 1,2-azaboretidinediimine **14**;[13] the structure of the product was investigated by X-ray diffraction (a study of **12** is lacking). Analogous behavior was shown by the aminoborane **15**; the product **16**, however, was accompanied by compound **17** which resulted from attack of unconsumed **15** on the four-membered ring; its amount increased as the reaction was prolonged.[14]

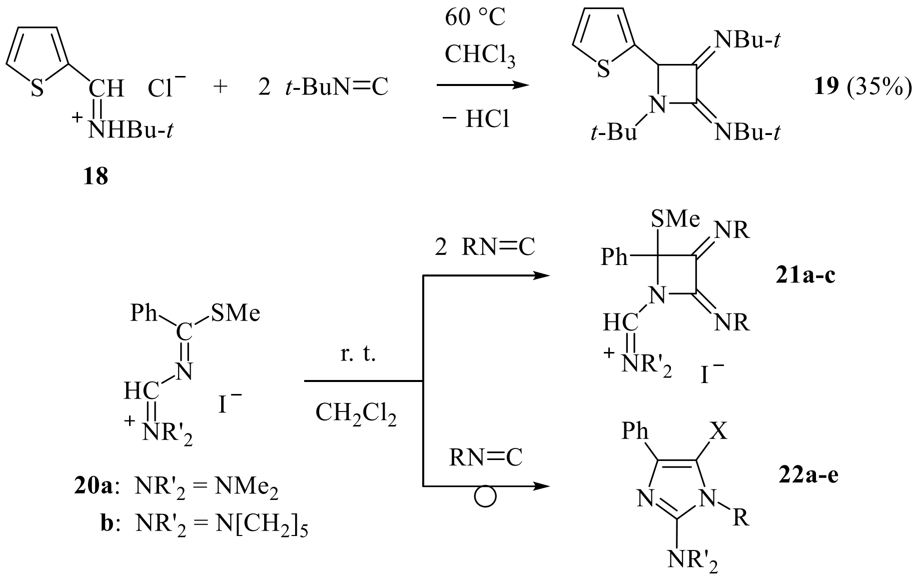


Scheme 3

Imines, thioimidates: A new example for addition of two isocyanide molecules across the C=N double bond of an imine is represented by the process **18** → **19** (Scheme 4). The experiment has been carried out along with studies on α,β-unsaturated imines which, however, afforded amino-pyrrole derivatives instead of analogs of **19**.[15] The thioimidate unit of the salts **20a,b** could be converted into an azetidine using *tert*-butyl and isopropyl isocyanide (→ **21a-c**). But a competing reaction gave the 2-aminoimidazoles **22a-e** (by involvement of the HC=NR'$_2$ moiety of **20**).[16]

2.2. [1+2] Cycloaddition of isocyanides to double bond systems and subsequent reactions

Diphosphenes: Experiments with this class showed that the resultant ring type depends on the substituents (Scheme 5): **23a** reacts with methyl or trifluoromethyl isocyanide to give the stable diphosphiranimines **24a,b**, whereas bis[2,4,6-tri-(*tert*-butyl)phenyl]diphosphene combines with the latter isocyanide in a 1:3 ratio to afford a 1,3-azaphospholidine derivative instead.[17] Three-membered rings like **24c,d** were also isolated when the metal-substituted diphosphene **23b** was reacted with phenyl or trifluoromethyl isocyanide; the same holds for the reaction of the latter component with the analogous substrate (**23c** → **24e**).[18] However, treatment of **23c** with several aryl[18] and alkyl isocyanides[19] led directly to 1,3-diphosphetanediimines like **25a-f**; the transient compounds **24f-k**, being prone to P–P fission (*cf.* Section 3.1), were detected spectroscopically.

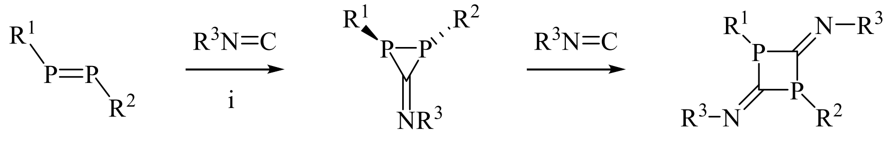


21, 22	R	NR'$_2$	X	RNC (mol)	Time (h)	Products (yield, %) / from
a	*t*-Bu	NMe$_2$	SMe	2	72	**21a** (8), **22a** (20), **22d** (42) / **20a**
b	*i*-Pr	NMe$_2$	SMe	5	18	**21a** (18), **22a** (55) / **20a**
c	*t*-Bu	N[CH$_2$]$_5$	SMe	5	18	**21b** (30), **22b** (44) / **20b**
d	*t*-Bu	NMe$_2$	H	2	48	**21c** (16), **22c** (28), **22e** (25) / **20a**
e	*t*-Bu	N[CH$_2$]$_5$	H	4	10	**21c** (25), **22c** (45) / **20b**

Scheme 4

Silenes: Photolysis of the acylsilane **26a** using 360-nm radiation generated the silene derivative **27a** (Scheme 6). In the presence of one equivalent of *tert*-butyl isocyanide (a) this compound underwent a [1+2] cycloaddition to give the siliranimine **28a** which in turn rearranged into the azasiliridine **29a**.[20,21] When a mixture of this material and 2,6-dimethylphenyl isocyanide (b) was photolyzed, the 1,3-azasiletidin-2-imine **30a** resulted.[22] Extending the experiments to the couples **27a** + (a), **27b** + (a), and **27b** + (b), the expected azasiliridines **29b-d** were formed, but these compounds, while eluding isolation, reacted with unconsumed isocyanide and produced the azasiletidines **30b-d**. However, under nonphotochemical conditions (–70 °C; dark) preformed **27a** and 2,6-dimethylphenyl isocyanide (b) gave rise to a mixture of the compounds **29b** and **30b**; this contrasts with the behavior of **27a** towards alkyl isocyanides (*cf.* above and ref.[20]), which leads exclusively to the type **29**. – Detailed NMR spectroscopic investigations of the products **30a-d** have shown the occurrence of two stereoisomers each for **a** and **b**, but only one for **c** and **d**. An X-ray diffraction study of the major isomer of **30b** has revealed a *Z* / *E* symmetry (C=N /

C=C group) as depicted; for brevity, this stereo formula was used here for **30a,c,d** as well. Yields of **30a-d** were not disclosed throughout.[22]



23a-c **24a-e,[f-k]** **25a-f**

i: 0 or 20 °C / (*n*-)pentane (for **24a-d**), 2-methylbutane (**24e**);
20 °C / benzene (for **25a,b**), toluene (**25d**), diethyl ether (**25e**), neat (**25f**)

23	24	25	R^1	R^2	R^3	Yield (%) [c]	*E* : *Z* [d]
a	**a**		$C(SiMe_3)_3$	$C(SiMe_3)_3$	Me	61	
	b		$C(SiMe_3)_3$	$C(SiMe_3)_3$	CF_3	63	
b	**c**		[Fe][a]	$C(SiMe_3)_3$	CF_3	31	
	d		[Fe]	$C(SiMe_3)_3$	Ph	63	
c	**e**		[Fe]	Mes*[b]	CF_3	54	
	f	**a**	[Fe]	Mes*	Ph	63	2 : 1
	g	**b**	[Fe]	Mes*	$2\text{-}MeC_6H_4$	48	2 : 1
	h	**c**	[Fe]	Mes*	$2,6\text{-}Me_2C_6H_3$		
	i	**d**	[Fe]	Mes*	C_6F_5	46	6 : 1
	j	**e**	[Fe]	Mes*	$c\text{-}C_6H_{11}$	57	2 : 1
	k	**f**	[Fe]	Mes*	CH_2Ph	79	2 : 1

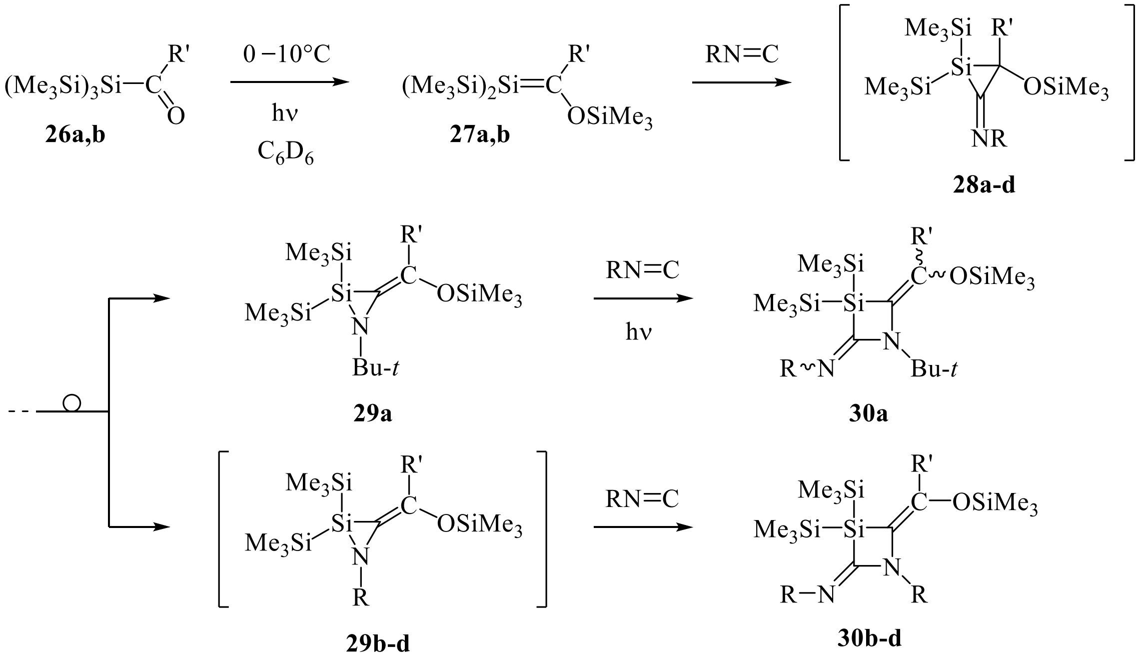
[a] [Fe] = $FeCp^*(CO)_2$. [b] Mes* = 2,4,6-(t-Bu)$_3C_6H_2$. [c] Products **24a-e** and **25a-f**, respectively (no yield for **25c**). [d] Two *Z* isomers observed.

Scheme 5

A later example of this kind of conversion constitutes the reaction of the neopentyl-substituted silene **27c**. This substrate – prepared from (dimesitylfluorosilyl)ethene and *tert*-butyllithium – gave the silazetidine **30e** on treatment with two equivalents of *tert*-butyl isocyanide.[23]

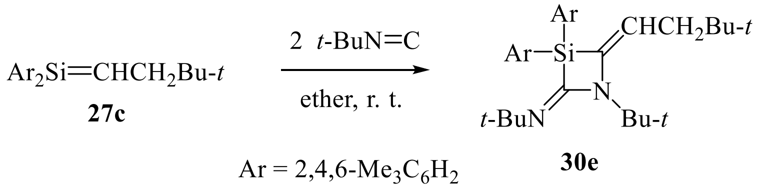
It might be added that azasiliridines related to **29** were obtained very recently from isocyanides and a disilene like $R_2Si{=}SiRPh$ [R = 2,4,6-(i-Pr)$_3C_6H_2$], but, remarkably, these products (which have a semicyclic C=Si bond instead of a C=C bond) did not undergo isocyanide insertion to give four-membered rings, *i.e.* silylidene analogs of **30**.[24]

Phospa-, arsasilenes: Unique derivatives of the type **30**, *i.e.* compounds like **32a-c**, arose quantitatively on exposure of the 'heterosilenes' **31a**[25] and **31b**[26] to mesityl and cyclohexyl isocyanide (Scheme 7). The reaction was assumed to follow the pattern of the preceding paragraph. Treatment of the products **32b,c** with hydrogen chloride (or fluoride), however, met with surprise in that arsasilete derivatives **33a,b** were isolated; X-ray crystallography served to establish the structures of both **32c** and **33b**.[26] Extending their ring forming experiments to 1,6-diisocyanohexane, the authors succeeded in converting **31a,b** into the corresponding macroheterocycles; of these new products, the arsa representative has also been studied by X-ray diffraction.[27]

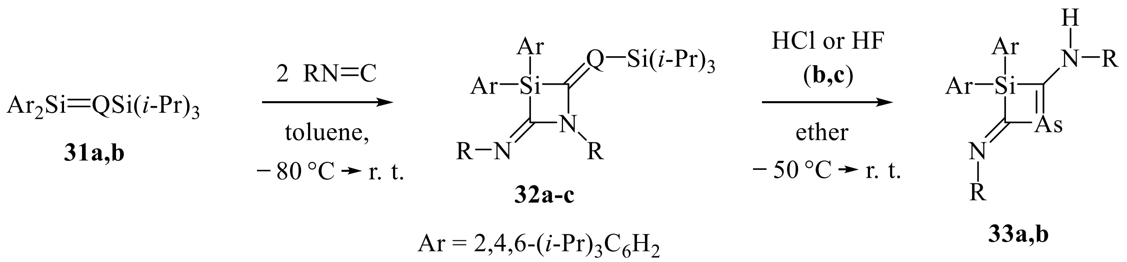


26, 27	**28, 29**	**30**	R	R'
a	**a**		*t*-Bu	1-Adamantyl
		a[a]	2,6-$Me_2C_6H_3$	1-Adamantyl
	b	**b**	2,6-$Me_2C_6H_3$	1-Adamantyl
b	**c**	**c**	*t*-Bu	2,4,6-$Me_3C_6H_2$
	d	**d**	2,6-$Me_2C_6H_3$	2,4,6-$Me_3C_6H_2$

[a] Compound **30a** isolated as mixed species of two geometric isomers in about 3:2 proportions.



Scheme 6



Ar = 2,4,6-(i-Pr)$_3$C$_6$H$_2$

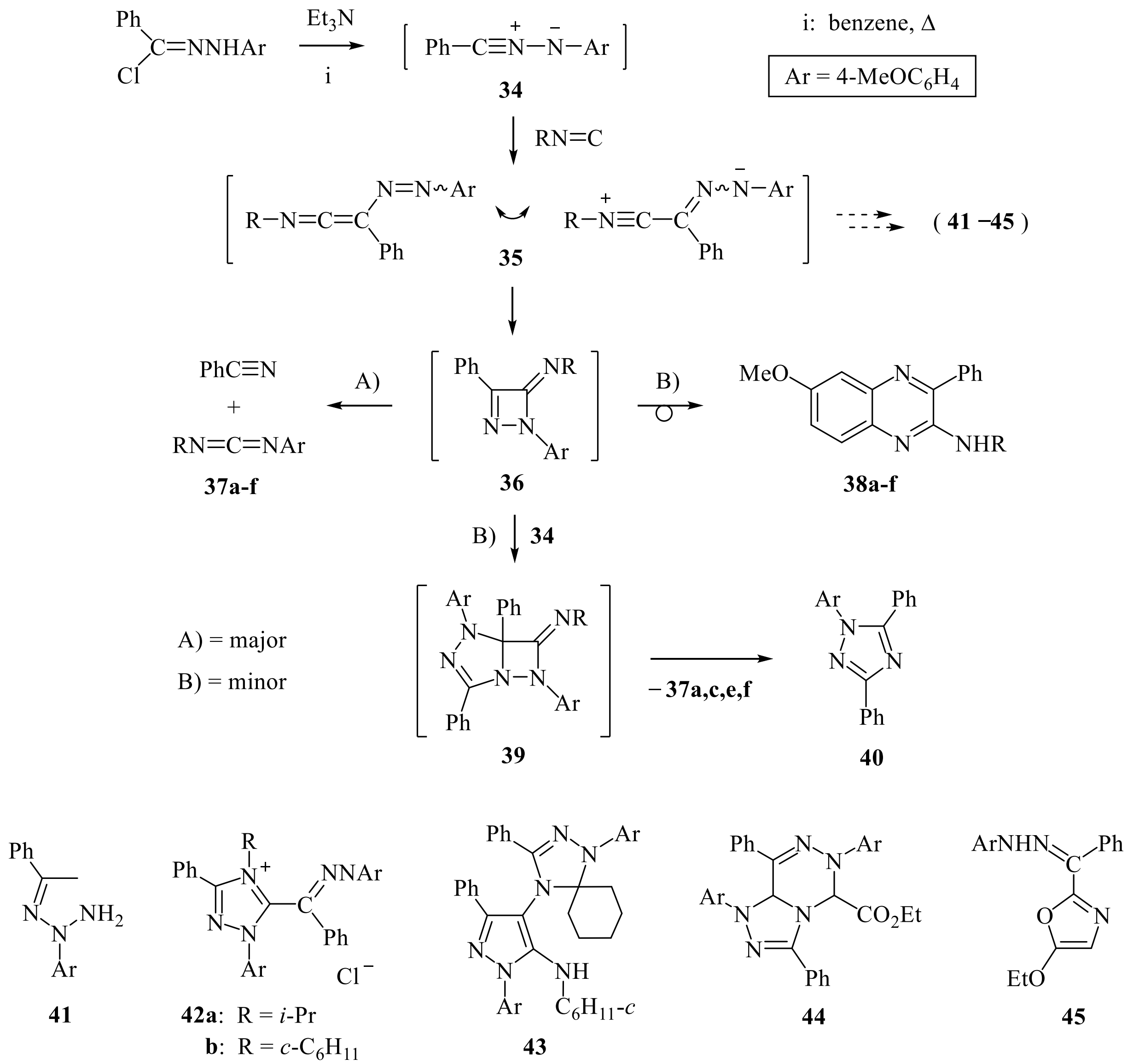
31	**32**	**33**	Q	R
a	**a**		P	2,4,6-Me$_3$C$_6$H$_2$
b	**b**	**a**	As	2,4,6-Me$_3$C$_6$H$_2$
	c	**b**	As	c-C$_6$H$_{11}$

Scheme 7

2.3. [1+3] Cycloaddition of isocyanides to 1,3-dipoles

Nitrile imines: Detailed studies on the behavior of *N*-aryl nitrile imines towards isocyanides[28–32] have shown that the title reaction occurred under certain conditions.[29,31,32] Best suited are nitrile imines bearing a donor-substituted phenyl group at the terminal nitrogen like **34**, they gave cycloadducts **36** with a wide variety of isocyanides (Scheme 8).[31,32] These four-membered rings, however, eluded isolation, but their formation could be inferred from products formed by [2+2] cycloreversion into benzonitrile and a carbodiimide (**37**), by ring expansion to a quinoxaline (**38**), and finally by [2+2] cycloreversion of the secondary adduct **39** into **37** and a 1,2,4-triazole (**40**). Besides these compounds products such as **41–45** were found; formally, they derive from the linear adduct **35** which in the case R = *t*-Bu could be detected spectroscopically.[33]

Compared to **34**, the proclivity of its *N*-phenyl analog to undergo a [1+3] cycloaddition is low,[29] and with Ar = 4-NO$_2$C$_6$H$_4$ there were no indications at all.[32] This failure applies also to nitrile imines having an acceptor group at the *C*-terminus like an acyl[31] or a 4-nitrophenyl substituent.[32]

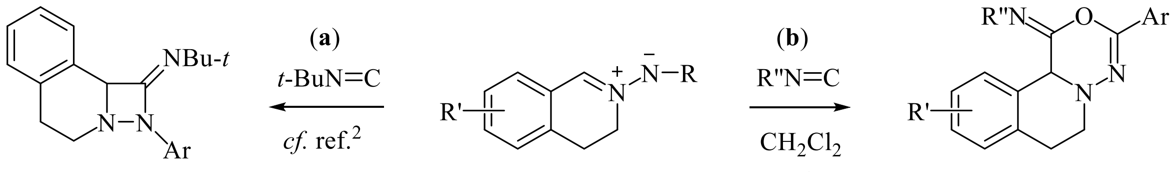


37	Yield (%) [a]	R	**38**	Yield (%)	Other / Yield (%)
a	49	*i*-Pr	**a**	15	**40** / 2, **42a** / 8
b	19	*t*-Bu	**b**	3	**41** [b] / 27
c	43	*c*-C_6H_{11}	**c**	25	**40** / 2, **42b** / 10, **43** / 6
d [c]		CH_2CO_2Et	**d**	18	**44** / 31, **45** / 7
e	37	4-$MeOC_6H_4$	**e**	21	**40** / 6
f	62	2,6-$Me_2C_6H_3$	**f**	17	**40** / 5

[a] Yield based on the respective urea. [b] By elimination of isobutene from transient 1-*tert*-butyl-2-(4-methoxyphenyl)-5-phenyl-2*H*-1,2,3-triazolium. [c] Carbodiimide **37d** apparently unstable.

Scheme 8

Azomethine imines: In contrast to the aryl functionalized CNN moiety in **46a** which, using *tert*-butyl isocyanide, was earlier cyclized to a 1,2-diazetidine ring (**47**),[2] the acyl group in the congener **46b**, as shown recently, confers upon the molecule a 1,5-dipolar character which led to the formation of a 1,3,4-oxadiazine cycle (**48**) (Scheme 9).[34]



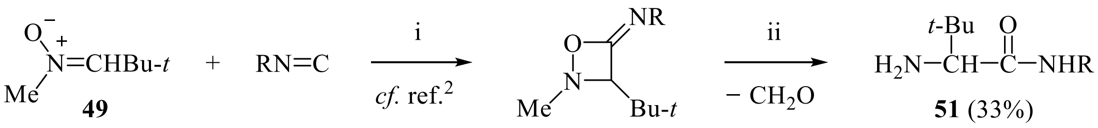
47 (51%)
Ar = 4-NO$_2$C$_6$H$_4$

46a: R = Ar, R' = H
b: R = COAr

48 (34−99%)
R" = Alk, Ar

Scheme 9

Nitrones: The known cyclization[2] of the nitrone **49** with cyclohexyl isocyanide to give the 1,2-oxazetidin-4-imine **50** has recently been duplicated for mechanistic purposes (Scheme 10).[35] To rationalize their synthesis of α-oxoamides from *N*-alkylhydroxylamines and aliphatic aldehydes under the conditions of the Ugi reaction, the authors thought of **50** as one possible intermediate and submitted this model to their procedure. But, being aware of an old observation,[36] they confirmed that N–O cleavage in **50** occurred with deprotonation of the *N*-methyl group (→ **51**), not at C(3) which would be necessary for the production of an α-oxoamide.



49

51 (33%)

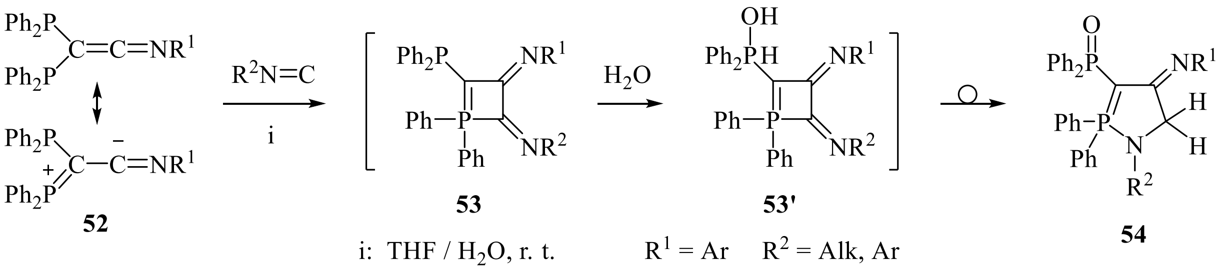
R = *c*-C$_6$H$_{11}$

50 (61%)

i: BF$_3$·OEt$_2$, then NEt$_3$; CH$_2$Cl$_2$, – 40 °C ii: AcOH, 4-Å MS, MeOH

Scheme 10

Diphosphinoketenimines: Although representing no classical 1,3-dipoles, the title substrates **52** were shown to behave as such (Scheme 11). In the presence of water they reacted with isocyanides to give compounds of the type **54** that were proposed to arise *via* four-membered rings like **53/53'**. Labeling experiments demonstrated that the oxygen and ring-attached hydrogen of **54** originate from the external water; in a rigorously dried medium no reaction occurred.[37]

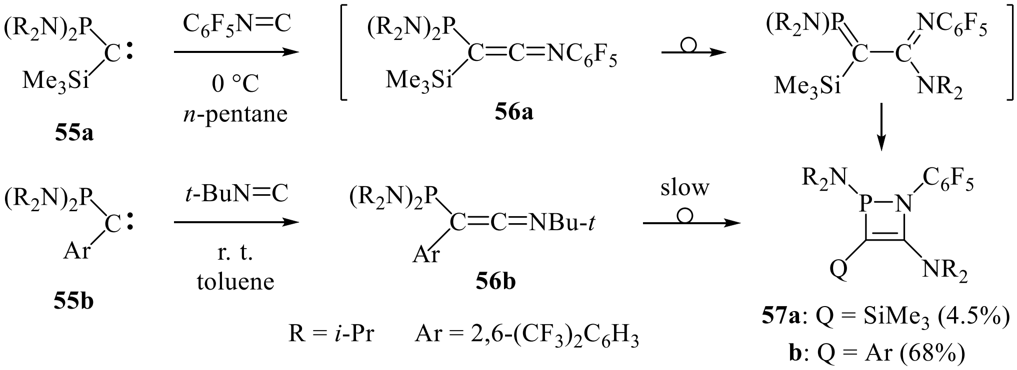


Scheme 11

(For 1,3-dipolar behavior of metal-coordinated ketenimines, see Section 2.5.)

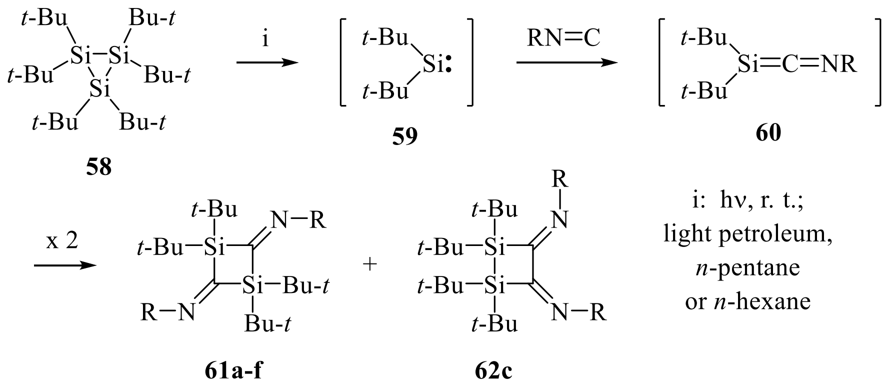
2.4. Addition of isocyanides to carbenes (including analogs) and subsequent reactions

Carbenes: The phosphino(silyl)carbene **55a**, generated from the corresponding diazo precursor, reacted with pentafluorophenyl isocyanide to give the dihydro-1,2-azaphosphete **57a**, which was established by an X-ray analysis (Scheme 12). The process was explained to involve a transient ketenimine (**56a**) that undergoes a P/→C/ migration of one NR_2 group, followed by electrocyclization of the resultant 1-aza-4-phosphabutadiene.[38,39] When reacting the arylsubstituted carbene **55b** with *tert*-butyl isocyanide, the respective ketenimine **56b** could be characterized spectroscopically, but at room temperature it rearranged slowly into the analogous ring system **57b**.[40]



Scheme 12

Silylenes: Photolysis of the trisilirane **58** in the presence of isocyanides has been shown to afford disiletanediimines of the type **61** and **62** (Scheme 13). These compounds arose by coupling of the silylene **59** with the isocyanide to give the silaketenimine **60** which in turn cyclodimerized. The reaction was performed with phenyl[41] and sterically crowded aryl isocyanides,[42] but also with isocyanides bearing electron-withdrawing groups.[43] As expected, head-to-tail cyclodimerization prevails; only when using 2,6-diisopropylphenyl isocyanide the head-to-head mode occurred too, giving minor amounts of the derivative **62c**.[42] While no yield figure was disclosed in that work, it was later detailed that the derivatives **61c** and **62c** were isolated in a ratio of *ca.* 10:1 (regardless of the reaction conditions) and that they were not interconverted photochemically.[44] The molecular geometry of **61a,c,d** and **62c** has been determined by X-ray crystallography.[41–43]

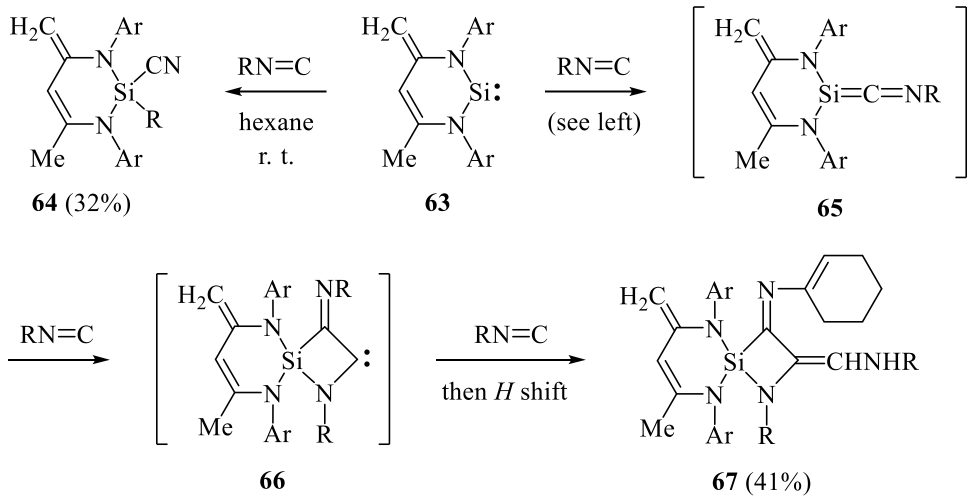


61 / 62	R	Yield (%)	61	R	Yield (%)
a	Ph	65	**d**	CF_3	72
b	2,4,6-$Me_3C_6H_2$	45	**e**	C_6F_5	50
c	2,6-(*i*-Pr)$_2C_6H_3$	76 / minor	**f**	3,5-$(CF_3)_2C_6H_3$	59

Scheme 13

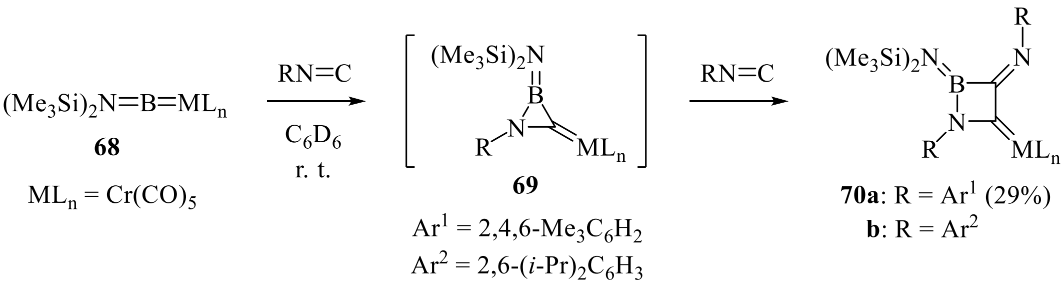
Surprising behavior was encountered with the (stable) silylene **63**. On treatment with cyclohexyl isocyanide two competing reactions occurred (Scheme 14): (i) α-addition of the CN and *c*-C_6H_{11} moieties of the fragmented reagent furnished the carbonitrile **64**; (ii) linear coupling of intact isocyanide led to the silaketenimine **65**; this intermediate, in contrast to species **60** (*cf.* Scheme 13), took up another isocyanide to generate a four-membered ring (→ **66**); stabilization of its carbene function by uptake of a third isocyanide, followed by hydrogen migration from the cyclohexylimino group, gave the product **67**, the structure of which was established by the X-ray method.[45]

Borylenes: An interesting borylene-to-isocyanide transfer resulting in the final formation of the four-membered rings **70a,b** happened when the chromium complex **68** was treated with certain aryl isocyanides (Scheme 15). The reaction assumedly involved a [1+2] cycloadduct (**69**) that was susceptive to isocyanide insertion. The molecular structure of **70a** was elucidated by X-ray diffraction.[46]

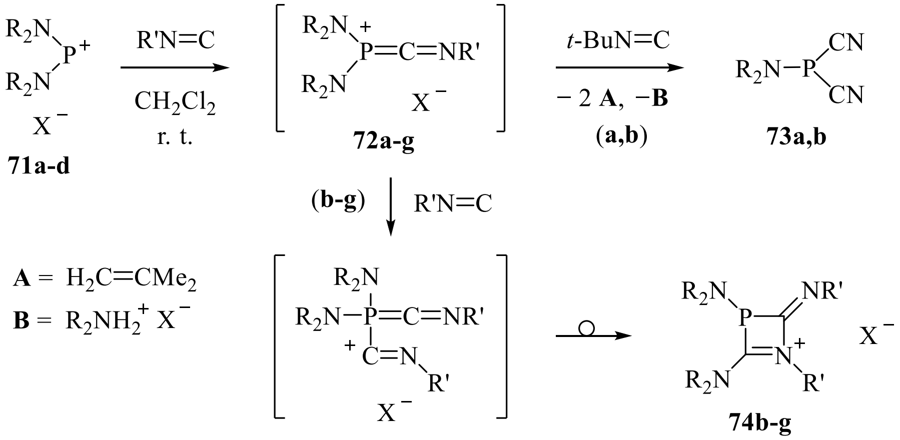


Ar = 2,4,6-$Me_3C_6H_2$ R = c-C_6H_{11}

Scheme 14



Scheme 15



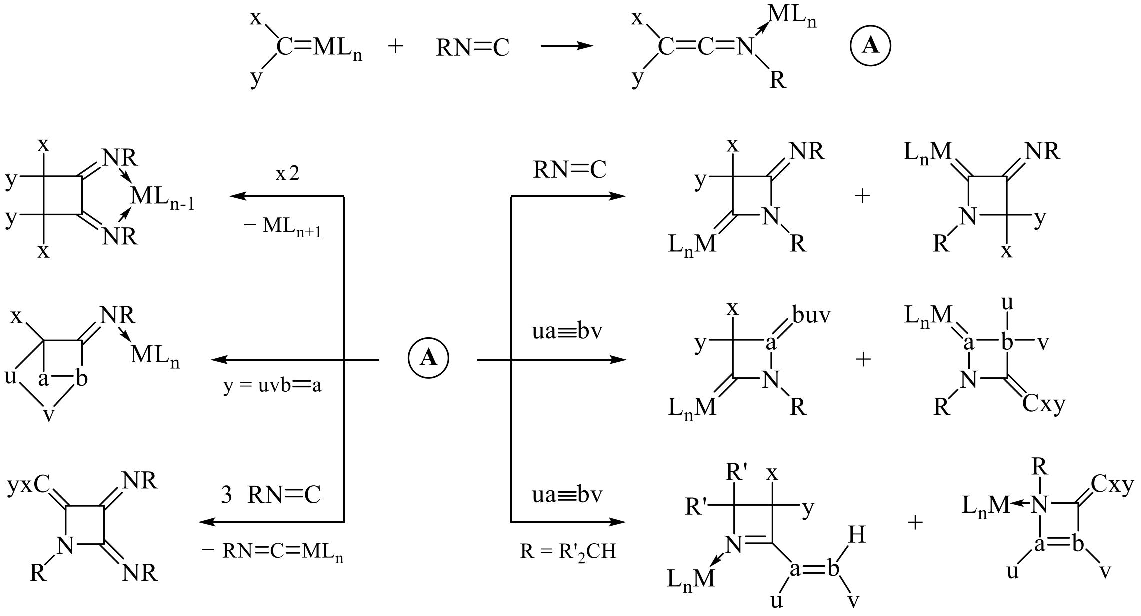
71 –74	R	R'	X	Yield (%)
a	i-Pr	t-Bu	CF_3SO_3	
b	Et	t-Bu	CF_3SO_3	50
c	Me	t-Bu	CF_3SO_3	92
d	Me	t-Bu	$AlCl_4$	89
e	Me	c-C_6H_{11}	CF_3SO_3	90
f	Et	c-C_6H_{11}	CF_3SO_3	80
g	i-Pr	c-C_6H_{11}	CF_3SO_3	90

Scheme 16

Phospheniums (Addendum): Carbenoid properties are also exhibited by phosphenium salts like **71a-d** (Scheme 16). These substrates couple with alkyl isocyanides to give transient phosphaketenimines (**72a-g**) which, depending on the substituents, react with a second molecule of isocyanide to afford either dicyanophosphine derivatives (**73a,b**) or imino-substituted dihydro-1,3-azaphosphetium salts (**74b-g**). When the intermediate **72b** took up *tert*-butyl isocyanide, both routes were followed so as to reduce the yield of the product **74b**.[47,48]

2.5. Addition of isocyanides to Fischer carbene complexes and subsequent reactions

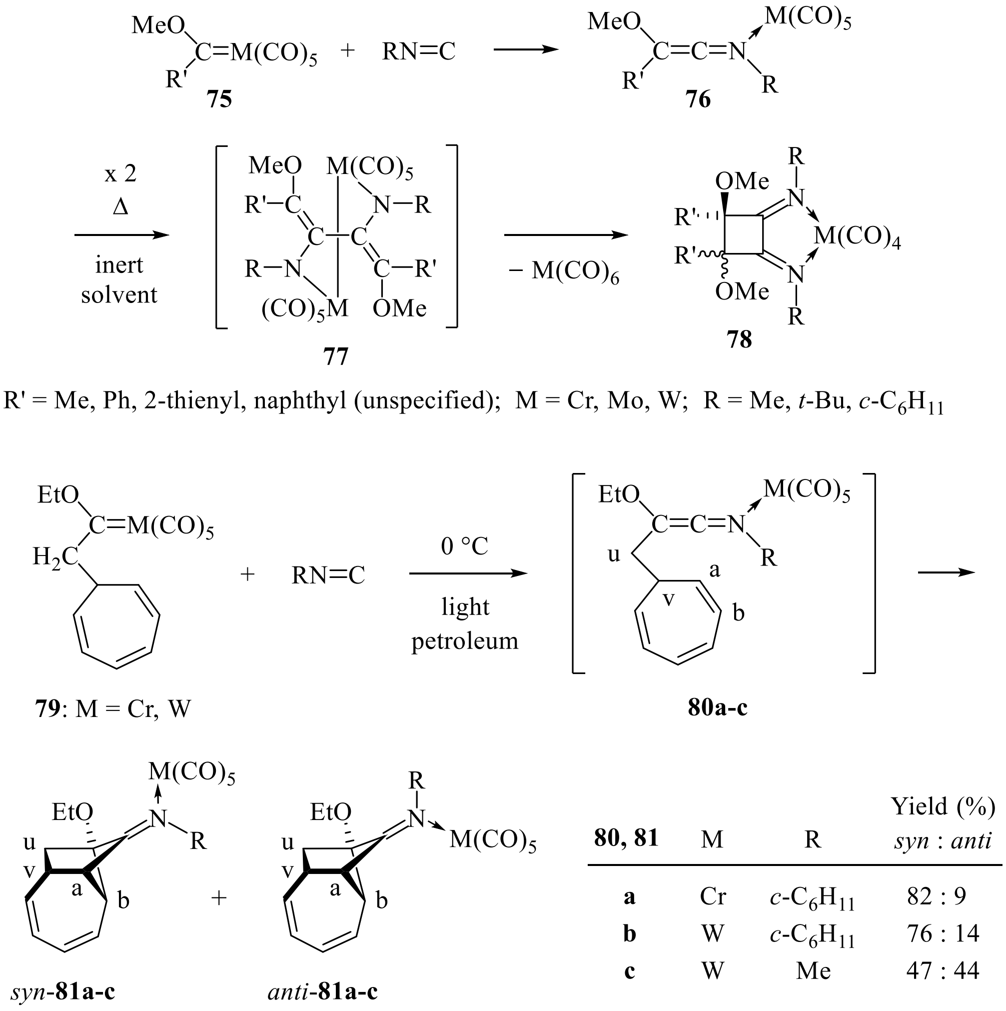
Isocyanides combine with Fischer-type carbenes to generate ketenimine complexes of the type **A** (Scheme 17). The mechanism of the process has recently been studied, showing that **A** is formed *via* a metallacyclopropanimine followed by isomerization and 1,2-metallotropic rearrangement.[49] Preparatively, these species have turned out to be valuable building blocks for a variety of four-, five-, and six-membered rings (for reviews, see refs.[50,51]). Concentrating on the first mentioned class, this section will describe applications of the synthetic principles outlined below. Beyond that, mention will be made of the ring contraction of a single [2+3] cycloadduct obtained from **A**.



Scheme 17

Dimerization: Carbene complexes such as **75** react with alkyl isocyanides to give the corresponding ketenimine complexes **76** (Scheme 18). On being heated in an inert solvent, these coupling products slowly dimerize to afford the metal-coordinated cyclobutanediimines **78**.[52–54] The symmetrical [2+2] cycloaddition which is unusual for free ketenimines is template-induced and thought to proceed through an intermediate like **77**. Part of this remarkable reaction has been reviewed earlier.[2]

Intramolecular cycloaddition: Ketenimine complexes bearing an alk-3-enyl moiety at the carbon atom like the derivatives **80a-c** undergo, once generated from the precursor **79**, an intramolecular [2_s+2_a] cycloaddition (Scheme 18). Owing to the involvement of the cycloheptatrienyl ligand, the cyclobutanimine unit becomes part of a tricyclic system, as illustrated by the products **81a-c**. Of these materials, two stereoisomers were found; the structure of *anti*-**81c** has been determined by X-ray crystallography. Attempts to demetalate this derivative with pyridine caused fragmentation of the four-membered ring.[55]

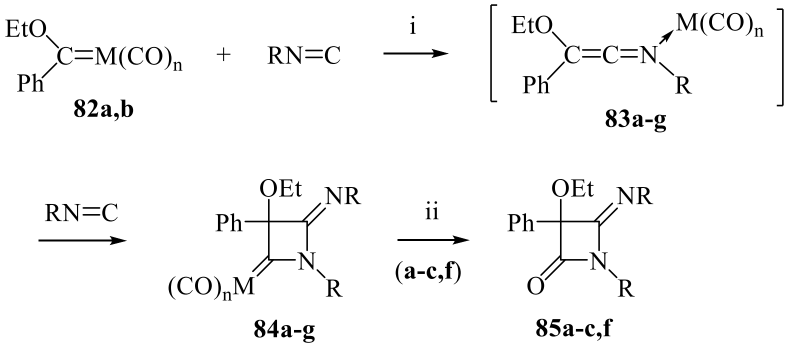


R' = Me, Ph, 2-thienyl, naphthyl (unspecified); M = Cr, Mo, W; R = Me, *t*-Bu, *c*-C_6H_{11}

80, 81	M	R	Yield (%) *syn* : *anti*
a	Cr	*c*-C_6H_{11}	82 : 9
b	W	*c*-C_6H_{11}	76 : 14
c	W	Me	47 : 44

Scheme 18

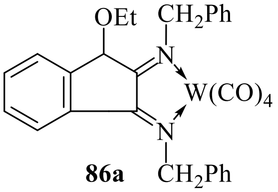
Addition of isocyanides: Ketenimine complexes exhibit 1,3-dipolaroid properties. Using isocyanides as dipolarophiles, 4-iminoazetidin-2-ylidene complexes can arise (Scheme 19). Success and extent of this reaction depend primarily on the metal. Thus, starting from the iron carbene complex **82a**, the desired products, *e.g.* **84a-d**, were obtained in high yield regardless of the nature of the isocyanide; the intermediary ketenimine complexes **83a-d** were not observed.[56,57] Yet, in the case of the tungsten complex **82b**, the [1+3] cycloaddition became a side reaction: Employing benzyl isocyanide, **84e** was accompanied by the indanediimine **86a** and the complex **87a**,[57] and using alkenyl isocyanides, relatively high quantities of the 2*H*-pyrroles **88a,b** were isolated besides the azetidinylidene complexes **84f,g**.[58] As the compounds **84** readily undergo oxidative demetalation, they are useful precursors to functionalized β-lactams (→ **85a-c,f**).[56,58]



i: light petroleum, r. t. (for **a-d,g**) or hexane, 0 °C (for **e,f**)
ii: KMnO$_4$, H$_2$O / C$_6$D$_6$, r. t. (for **a-c**) or pyridine *N*-oxide, toluene, Δ (for **f**)

					Yield (%)[c]		
82	**83−85**	M	n	R	**84**	**85**	Other / Yield (%)
a	**a**	Fe	4	Me	94	95	
	b	Fe	4	Ph	96[a] / 76[b]		
	c	Fe	4	*c*-C$_6$H$_{11}$	94[a] / 77[b]		
	d	Fe	4	CH$_2$Ph	80[b]		
b	**e**	W	5	CH$_2$Ph	7		**86a** / 10, **87a** / 14
	f	W	5	CH=CH$_2$	20	88	(*Z*)-**88a** / 50, (*E*)-**88a** / 10
	g	W	5	CH=CHR	31		(*Z*)-**88b** / 52, (*E*)-**88b** / 10

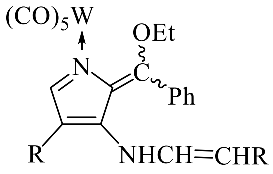
[a] Ref.[56] [b] Ref.[51] [c] No yield figures for **85b,c** (formed without side materials).[56]



86a

PhCH$_2$N=C=W(CO)$_5$

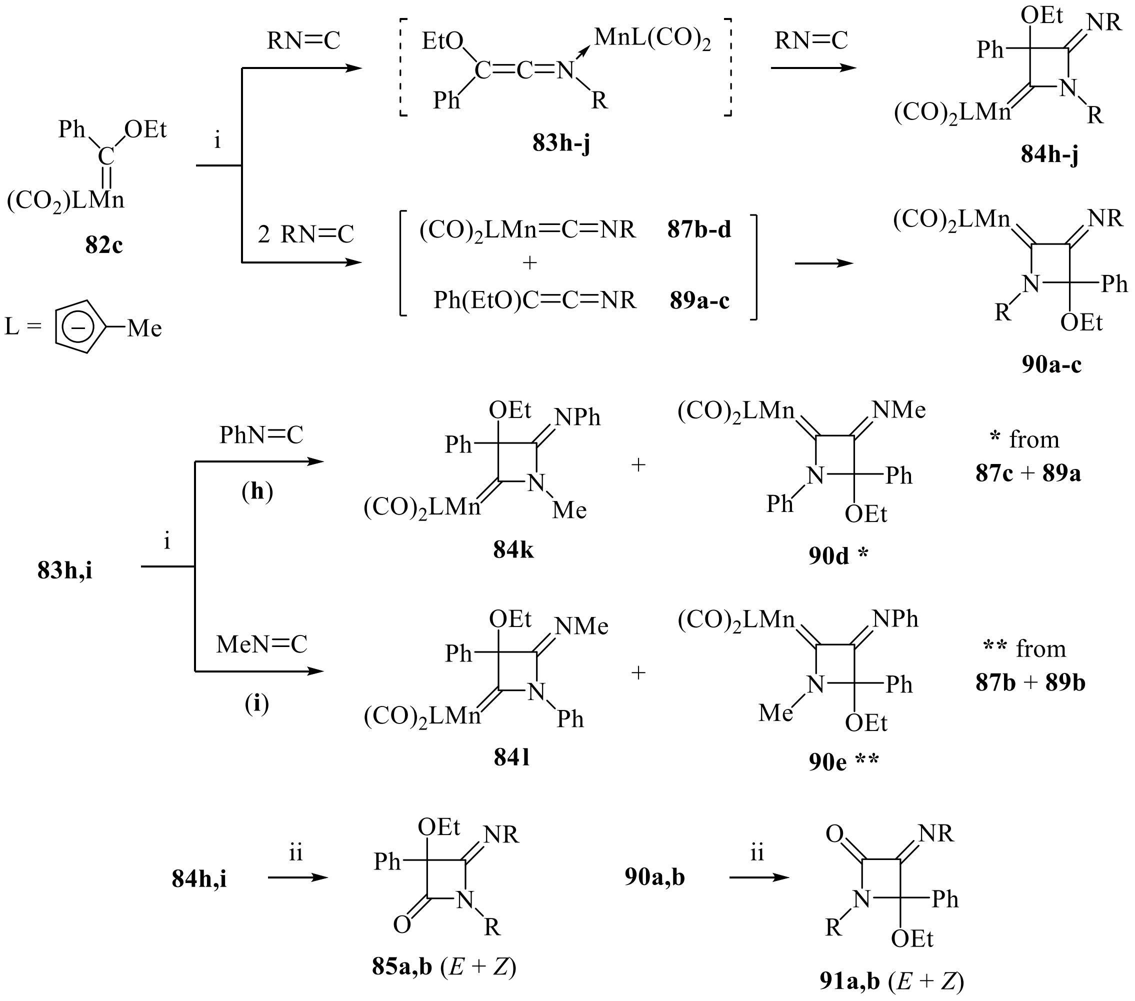
87a



88a: R = H **b**: R = Me

Scheme 19

Further derivatives **84** could be prepared from the manganese complex **82c** (Scheme 20).[59] This species is less reactive towards isocyanides than the substrates **82a,b**. Moreover, the excess isocyanide which is necessary for ring closure tends to displace the metal from the ketenimine complex **83** to leave a mixture of the isocyanide complex **87** and the free ketenimine **89**. As a consequence of this competing process, the 'regular' products **84h-j** were accompanied by [2+2] cycloadducts like **90a-c**; the proportions varied with the conditions and the kind of isocyanide. Since the conversion **83** → **84** proceeds more slowly than the step **82c** → **83**, it was also possible to construct azetidinylidene complexes **84** (including the type **90**) from two different isocyanides; this is exemplified by the couples **84k / 90d** and **84l / 90e**. Representatives of both ring series such as **84h,i** and **90a,b** could be demetalated with permanganate salt to give the β-lactams **85a,b** and **91a,b**, respectively.[59]

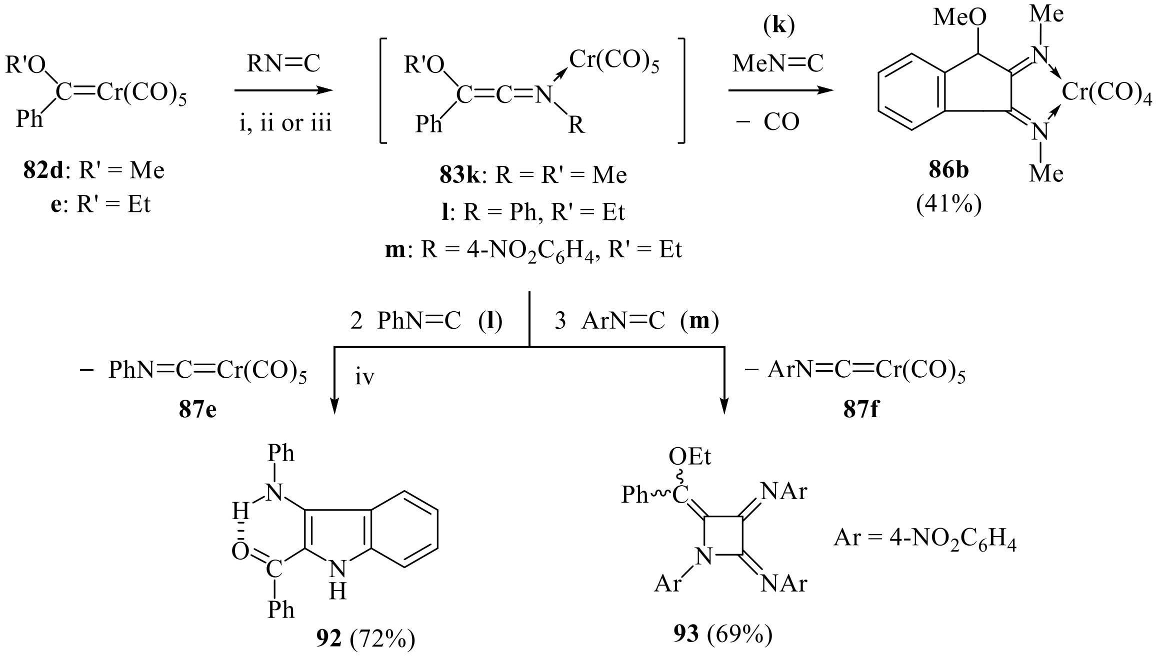


i: toluene, Δ ii: $KMnO_4$, diethyl ether / H_2O, r. t.

83, 84	R	87	89 – 91	Yield (%) 84 / 90	Conditions
h	Me	**b**	**a**	30 [4] / 15 [25]	60 °C (4 h) → 100 °C (3 h) [100 °C (4 h)]
i	Ph	**c**	**b**	67 [37] / 4 [10]	60 °C (4 h) → 100 °C (3 h) [100 °C (4 h)]
j	CH_2Ph	**d**	**c**	29 / trace	100 °C (3.5 h)

Scheme 20

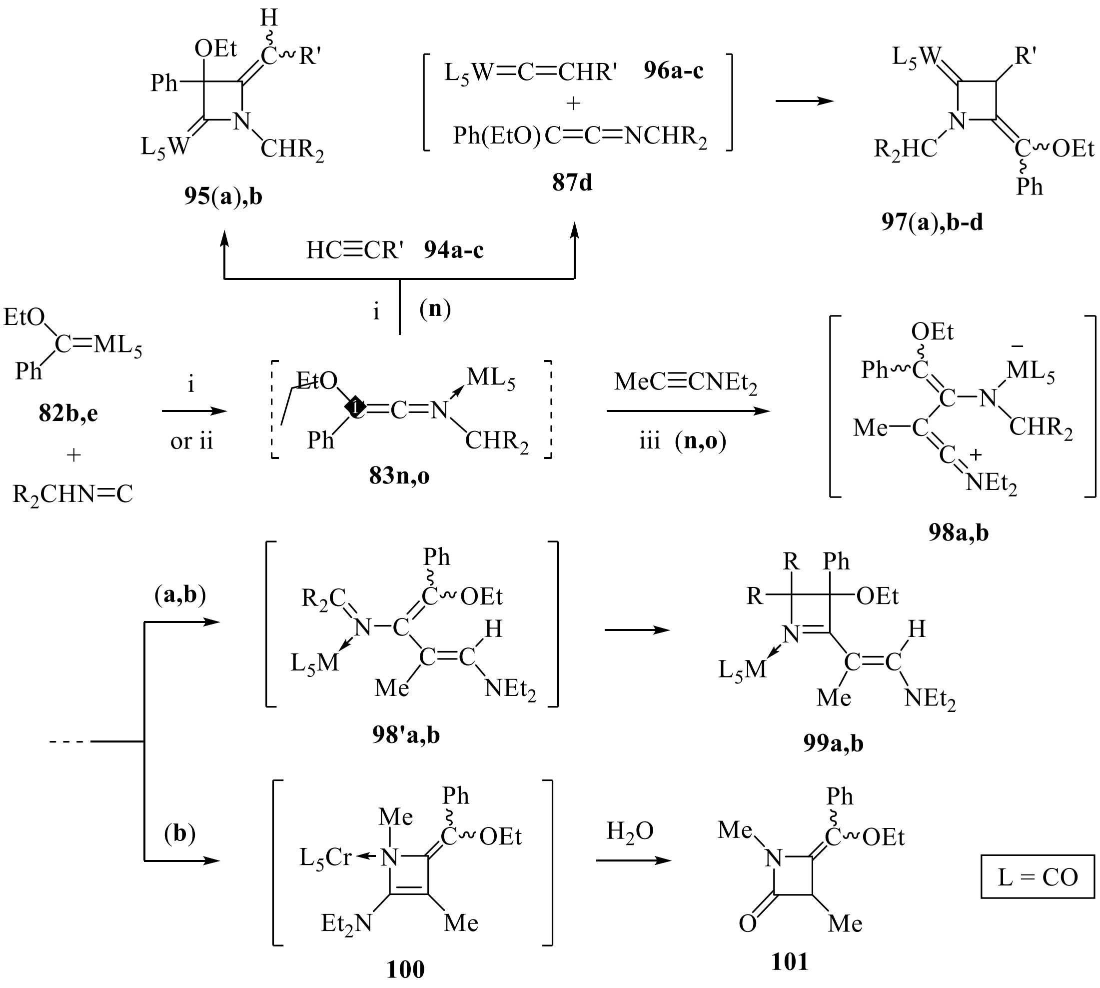
In contrast to the ketenimine complexes **83a-j** dealt with above, analogs prepared from the chromium complexes **82d,e** did not undergo [1+3] cycloadditions with isocyanides (Scheme 21). After **83k,l** have taken up methyl and phenyl isocyanide, respectively, cyclization engaged the *C*- and *N*-attached aryl groups to give the indane-2,3-diimine **86b**[60] and – through hydrolysis of the enol ether – the 3-aminoindole **92**.[54,61] However, in the case of 4-nitrophenyl isocyanide, *i.e.* with the intermediary 1:1 adduct formed from **83m**, generation of an indole is impeded because of the electron-withdrawal exerted by the nitro group; hence, a further isocyanide molecule will attack to eventually afford the azetidine-2,3-diimine **93** – formally a [1+1+2] cycloadduct of two isocyanides and one ketenimine (for another rare example, *cf.* ref.[2]).



i: light petroleum, 0 °C (for **k**) ii: THF, Δ (for **l**) iii: CH_2Cl_2, r. t. (for **m**) iv: H_2O

Scheme 21

Addition of alkynes: a) Alk-1-ynes: Two types of 4-ylideneazetidin-2-ylidene complexes arise, when the second isocyanide that effects ring closure to **84** and **90** (*cf.* Scheme 19, 20) is replaced with a 1-unsubstituted alk-1-yne (**94**) (Scheme 22). Heating an equimolar mixture of **82b**, cyclohexyl isocyanide, and (trimethylsilyl)ethyne (**94a**), the four-membered rings **95a** and **97a** were formed (isolated as the silicon-free derivatives **b**). While the process leading to **95** can be compared to that giving **84**, the formation of **97** resembles the route to series **90**; the vinylidene complexes **96** – putative intermediates – may arise directly from **82b**. Using alkynes like **94b,c**, only the derivatives **97c,d** were found, with the *Z* isomer predominating.[62]



i: toluene, Δ (for **n**) ii: petroleum ether, r. t. (for **n**) or 0 °C (for **o**) iii: benzene, r. t.

82	83	**94** **96**	**95** **97**	**98** **99**	M	R, R	R'	Yield (%) (**95** / **97**)	*E* : *Z* (**97**)	Yield (%) (**99**)
b	**n**	**a**	**a** [a]	**a**	W	$[CH_2]_5$	$SiMe_3$			23
e	**o**			**b**	Cr	H, H				13
			b			$[CH_2]_5$	H	10 / 13	2 : 3	
		b	**c**			$[CH_2]_5$	CH_2OMe	0 / 18	1 : 2	
		c	**d**			$[CH_2]_5$	Ph	0 / 28	1 : 12	

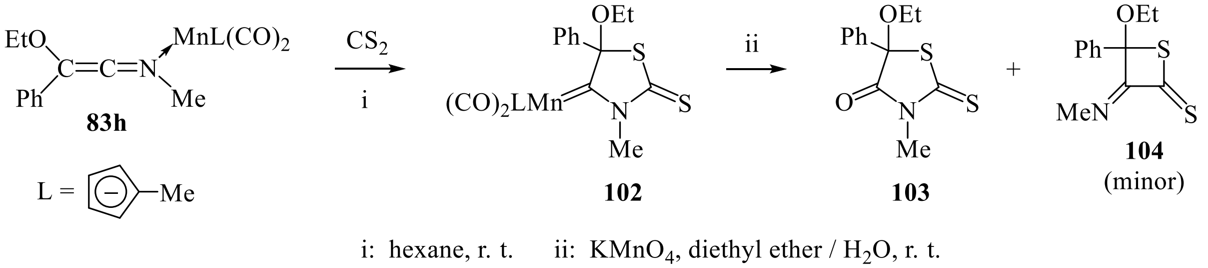
[a] Products **95a** and **97a** were hydrolyzed to **95b** and **97b** during work-up.

Scheme 22

b) Ynamines: The reaction of the ketenimine complexes **83** with the electron-rich diethyl-(prop-1-ynyl)amine took an unexpected course: Treatment of **83n,o** (isolated pure) furnished the 2,3-dihydroazete complexes **99a,b** (Scheme 22). Here four atoms of the original ketenimine unit were incorporated into the product (the structure of **99b** was studied by X-ray crystallography).

Mechanistically, the reaction was understood as proceeding through an adduct of the type **98**; in this species a hydrogen transfer from the CHR_2 group to the central keteniminium carbon took place to generate the intermediate **98'** which underwent electrocyclization. In the case of **98b**, a second mode was operative, *i.e.* intramolecular [2+2] cycloaddition to the 1,4-dihydroazetidine complex **100** which on work-up was hydrolyzed to the β-lactam **101** (no yield).[63]

Ring contraction (Addendum): An unexpected formation of a four-membered ring was encountered when the [2+3] cycloadduct **102** from the ketenimine complex **83h** (for prepration, see Scheme 20) and carbon disulfide was oxidized with aqueous permanganate (Scheme 23). Besides the regular product – the thiazolidin-5-one **103** – small amounts of the 3-iminothietane-2-thione **104** were detected; formally, this material arose through ring contraction of 'deoxygenated' **103**. Both compounds were formed in a 20:1 ratio with a total yield of 96% (crude).[64]

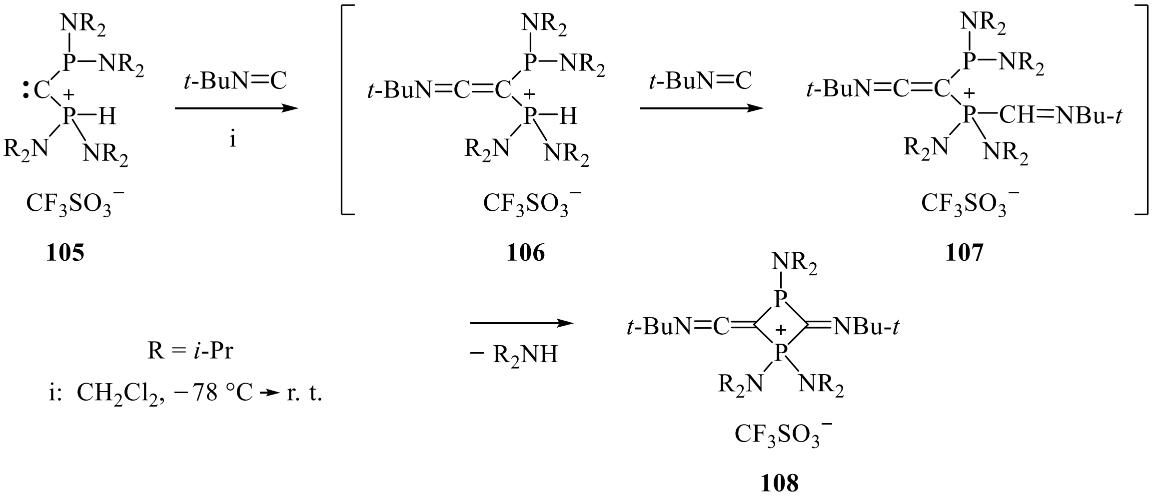


Scheme 23

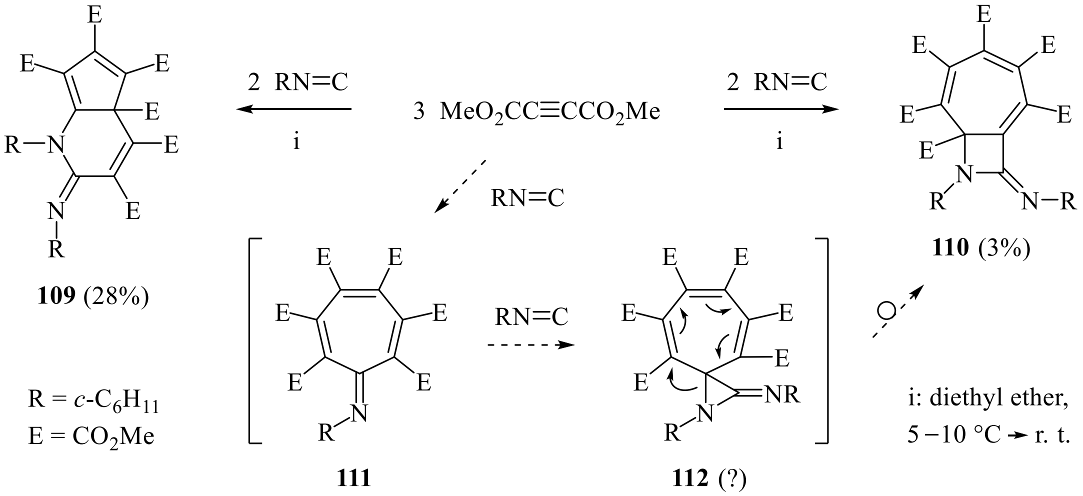
2.6. Miscellaneous

Functionalized phosphino(phosphonio)carbene: Treatment of the salt **105** with two equivalents of *tert*-butyl isocyanide gave rise to the 1,3-diphosphetanium ring as in **108** (no yield); employment of only one equivalent led to the recovery of 50% of the starting substrate (Scheme 24).[65] The reaction commenced with formation of the ketenimine **106**; but, while stable when unprotonated (*cf.* ref.[66]), this species rapidly inserts the second isocyanide into the P–H bond to give an intermediate like **107** which underwent ring closure through elimination of diisopropylamine.

Butynedioic acid ester: It is known that reactions of isocyanides with dimethyl butynedioate (DMAD) do not follow the pattern of Section 2.1, *i.e.* giving cyclobutenediimines.[2] However, a four-membered ring may arise from that reagent by another route. Indeed, a more recent study using cyclohexyl isocyanide has shown that – besides the cyclopenta[*b*]pyridine **109** (including minor quantities of an isomer and a 1-azaspiro[4.4]nonatriene) – the cyclohepta-anellated azetidinimine **110** was formed (Scheme 25).[67,68] As a direct precursor the 3:1 cycloadduct of DMAD and the isocyanide, *i.e.* the cycloheptatrienimine **111**, has been invoked.[67] To rationalize its conversion into **110**, a transient species like **112** is added here tentatively. Ensuing work of other authors concentrated on the preparation of **109** (including an X-ray study of the product); additional compounds were not reported.[69]

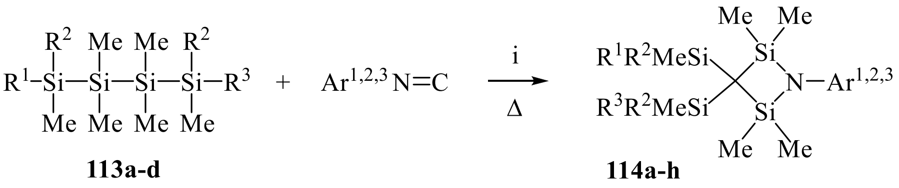


Scheme 24



Scheme 25

Oligosilanes: Insertion of isocyanides into the Si–Si bond involving a unique skeletal rearrangement has been encountered when the tetrasilanes **113a-c** and the hexasilane **113d** were reacted with certain aryl isocyanides in the presence of a palladium catalyst and 1,1,3,3-tetramethylbutyl isocyanide (**115**) (Scheme 26). This procedure gave the 1,2,4-azadisiletanes **114a-g** and **114h**, respectively.[70,71] The structures of **114c**[70] and **114h**[71] have been elucidated by X-ray crystallography. Regarding the *tert*-alkyl isocyanide **115**, this additive, without entering the four-membered ring, has proved an effective promotor in most cases as evidenced by comparison of the yields.[71]


113a-d

114a-h

$Ar^1 = 2,6\text{-}Me_2C_6H_3$ $Ar^2 = 2,6\text{-}(i\text{-}Pr)_2C_6H_3$ $Ar^3 = 2\text{-}MeC_6H_4$

i: $Pd(OAc)_2$, 10 mol%; $t\text{-}BuCH_2CMe_2NC$ (**115**); toluene

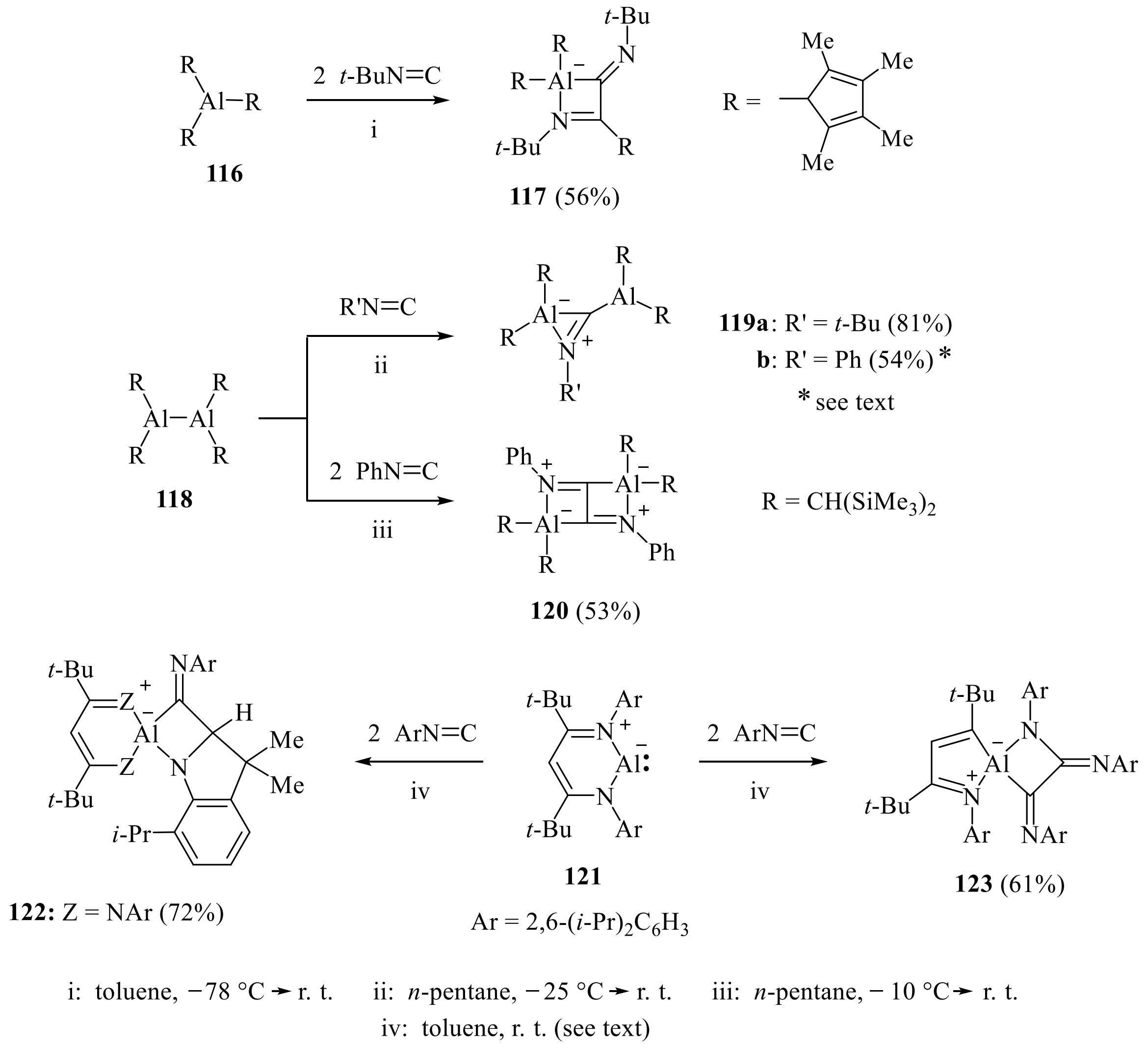
113	R^1	R^2	R^3		**114**	Yield (%) [**115**: yes / no]
a	Me	Me	Me	Ar^1	**a**	40 / 9
	Me	Me	Me	Ar^2	**b**	45 / 40
b	Ph	Me	Ph	Ar^1	**c**	31 / 37
	Ph	Me	Ph	Ar^2	**d**	62 / 50
	Ph	Me	Ph	Ar^3	**e**	24 / 0
c	Ph	Ph	Ph	Ar^1	**f**	28 / 10
	Ph	Ph	Ph	Ar^2	**g**	48 / 54
d	$SiMe_2SiMe_3$	Me	Me	Ar^2	**h**	15 / −

Scheme 26

Organoaluminum compounds: *tert*-Butyl isocyanide was found to undergo double insertion into one Al–C bond of tris(tetramethylcyclopentadienyl)aluminum (**116**) to form the four-membered ring **117** (Scheme 27). The cyclic structure has been elucidated by X-ray diffraction. The strong Al–N linkage seems to be the driving force behind the twofold insertion which is favored to such an extent as to leave unreacted **116** when working with less than two equivalents of isocyanide.[72]

Insertion of isocyanides into the Al–Al bond of the dialane **118** resulted in the formation of a three- or four-membered ring, depending on the reagent and conditions. Using one equivalent of *tert*-butyl isocyanide, compound **119a** was obtained as the single product. However, phenyl isocyanide not only afforded the expected derivative **119b**, but also gave 17% of the product of double insertion, *i.e.* the bicyclic system **120**. Hence, on repeating the experiment with two equivalents of this isocyanide, compound **120** was isolated exclusively. An analogous run with *tert*-butyl isocyanide was not reported.[73]

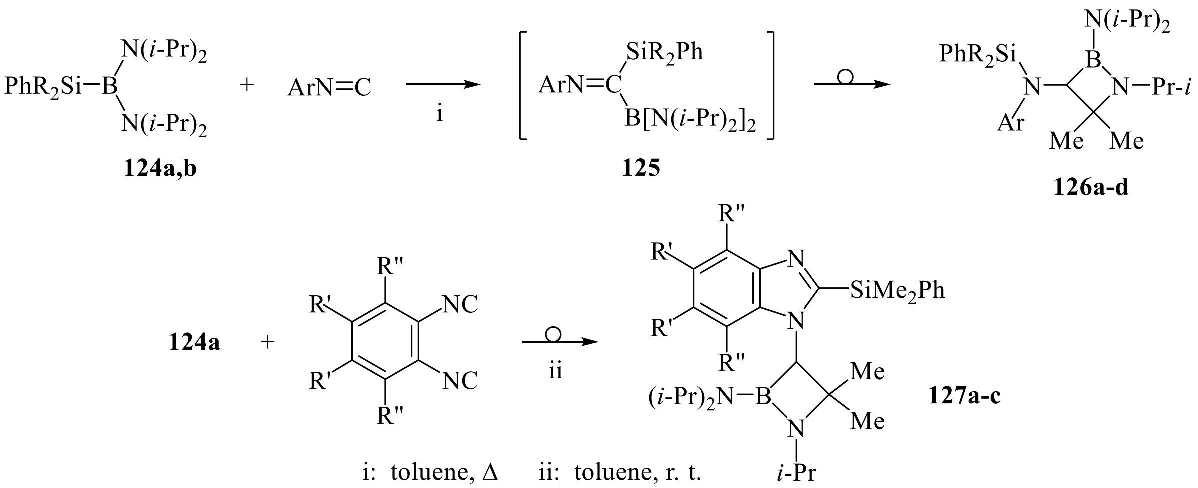
The aluminum(I) complex **121** (dealt with in this section for practical reasons) was found to react very readily with two equivalents of 2,6-diisopropylphenyl isocyanide. When this reagent was added neat to a suspension of **121** in a minimum amount of solvent, the remarkable compound **122** was isolated. Its formation was thought to proceed through consecutive coupling of both isocyanides leaving a four-membered ring, the carbenic C(4) of which interfered with the adjacent isopropyl group to give the stable product **122**. When working in a dilute medium, compound **123** arose, possibly *via* insertion of the two isocyanides into one of the Al–C bonds to be followed by a skeletal rearrangement of the resultant eight-membered ring. The structures of **122** and **123** have been determined by X-ray crystallography.[74]



Scheme 27

(Diaminoboryl)silanes: Insertion of an aryl isocyanide into the Si–B bond of the borylsilanes **124** generates (boryl)(silyl)iminomethanes (**125**) (Scheme 28). Compounds of this type, *e.g.* **125a** (R= Me, Ar = 3,5-$Me_2C_6H_3$), are obtained in high yield when working at room temperature. However, in refluxing toluene an unexpected rearrangement took place, consisting in a 1,2-shift of the silyl group to leave an (amino)(boryl)carbene species which engaged an adjacent isopropyl group to form the 1,2-azaboretidine **126a**.[75] The reaction was shown to be limited to isocyanides having a free *ortho*-position. Thus, while the reaction of **124a** with 2,6-dimethylphenyl isocyanide even at 110 °C did not go beyond the stage of insertion (**125**), four-membered rings like **126b-d** were formed readily from a range of 2-alkynylphenyl isocyanides. Extending the experiments to 1,2-diisocyanobenzenes, only one –N=C group reacted with the substrate to give the benzimidazolyl substituted azaboretidines **127a-c**; the two derivatives **a,b** having R" = H were obtained at room temperature. X-ray crystallographic data are available for the products **126d** and **127a**.[75]

Tris(trimethylsilyl)silyllithium: The silyllithium substrate **128** was found to react smoothly with two molecules of 2,6-dimethylphenyl isocyanide to form, in the presence of *N,N,N',N'*-tetramethylethylenediamine (tmeda), the 1,2-dihydro-1,2-azasilete derivative **129** (Scheme 29).[76] The process assumedly started with the formation of a lithioaldimine followed by migration of one silyl group to generate a silene species which incorporated the second isocyanide *via* electrocyclization. Quenching of **129** with trimethylsilyl triflate afforded the derivate **130**,[76] while treatment with cyclopentadiene yielded the conjugated acid **131**.[77] Moreover, reacting **128** in the presence of the soft 1,2-bis(dimethylphosphino)ethane gave a product **129** having THF instead of tmeda.[77] Detailed X-ray diffraction studies have been conducted with both **129** and **131**.[76,77]

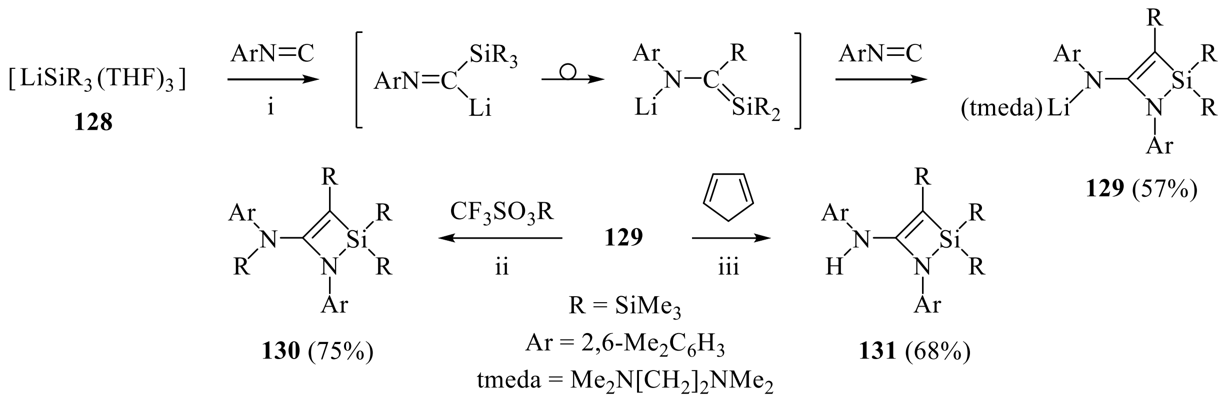


124	126	127	R	R'	R"	Ar	Yield (%) 126	Yield (%) 127
a	**a**	**a**	Me	H	H	3,5-$Me_2C_6H_3$	76	71[a]
	b	**b**	Me	Me	H	2-($Me_3SiC{\equiv}C$)C_6H_4	86	54[a]
	c	**c**	Me	H	Me	2-(t-$BuC{\equiv}C$)C_6H_4	82	
b	**d**		Ph			2-($Me_3SiC{\equiv}C$)C_6H_4	84	

[a] Adduct with BH_3.

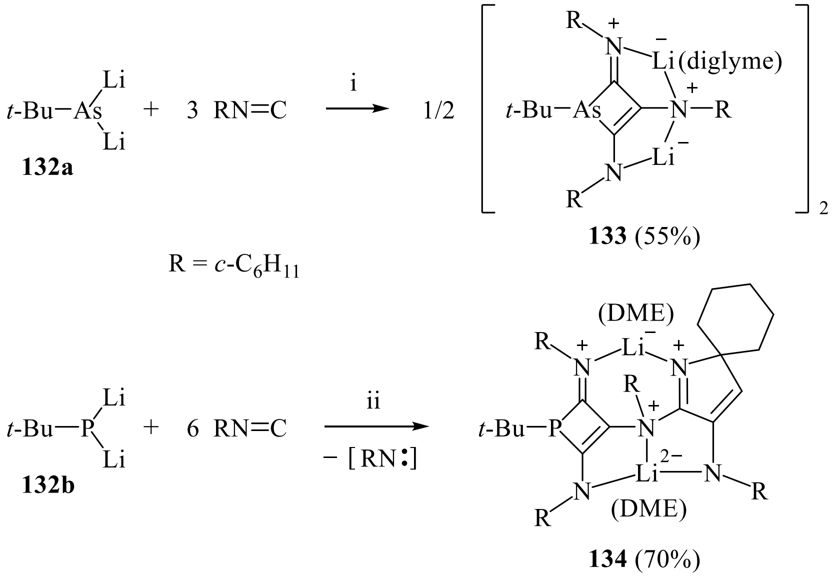
Scheme 28

Dilithium tert-butylarsinide and -phosphinide: Action of the arsenic compound **132a** on cyclohexyl isocyanide caused trimerization of the latter to form the product **133** which was isolated after addition of cyclohexane and diglyme (Scheme 30). By contrast, usage of the phosphorus analog **133b** led to an engagement of six equivalents of the isocyanide to generate the more complicated structure **134** and, as a side product, an open-chain material originating from cyclohexylnitrene. The constitution of both cyclic products has been established by X-ray analyses.[78]



i: pentane, tmeda, − 80 °C → r. t. ii: pentane, − 40 °C → r. t. iii: pentane, − 60 °C → r. t.

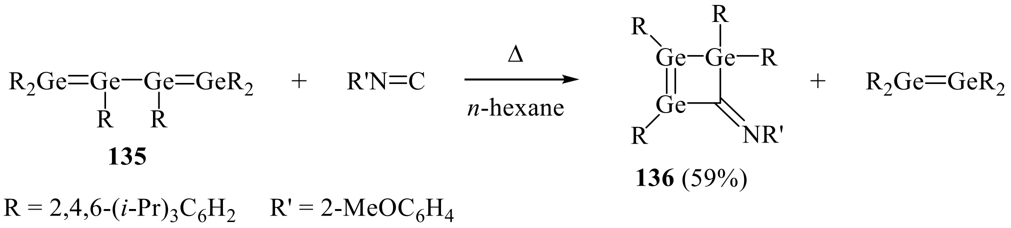
Scheme 29



i: THF, 20 °C; then diglyme/*c*-hexane ii: THF, 20 °C; then DME

Scheme 30

Tetragermabutadiene: Studies on the behavior towards the heavy chalcogens selenium and tellurium have revealed that the title substrate **135** (Scheme 31) is capable of undergoing [1+4] cycloadditions or Ge–Ge bond scissions, depending on the reagents. The former mode was followed by selenium, whereas treatment with tellurium caused fragmentation of the substrate. In this context the reaction with 2-methoxyphenyl isocyanide was probed too, showing that one Ge–Ge bond was broken: while the extruded germylene dimerized, the residual Ge_3 chain cyclized to the 1,4-dihydrotrigermet-4-imine **136** which was characterized by X-ray crystallography.[79]



Scheme 31

3. Reaction of isocyanides with cyclic substrates

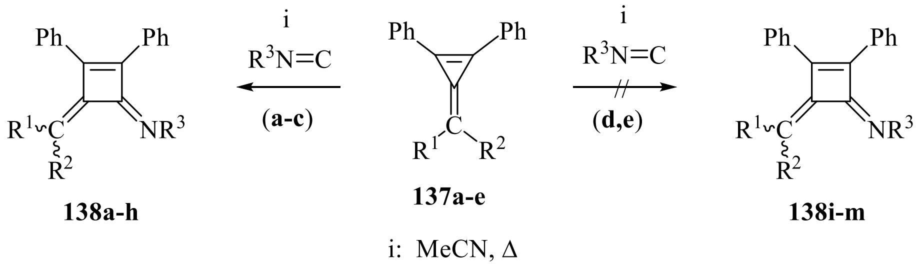
3.1. Insertion of isocyanides into three-membered rings

Triafulvenes: In a fashion similar to the behavior of cyclopropenones towards isocyanides,[2] the triafulvenes **137a-c** underwent ring expansion to the 2-ylidenecyclobutenimines **138a-h** when treated with the respective isocyanides in an aprotic medium (Scheme 32).[80]

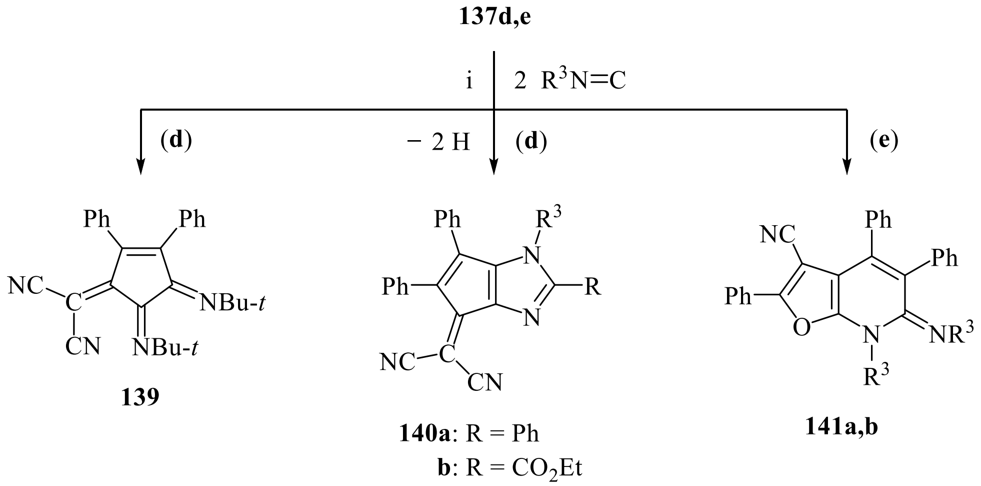
From the substrates **137d,e**, however, four-membered rings such as **138i-m** could not be obtained. In this instance two equivalents of the isocyanide were engaged to afford, depending on the substituents R^1, R^2, and R^3, (i) the cyclopentenediimine **139** or the azapentalenes **140a,b** (which were formed through intramolecular dehydrogenation of a precursor like **139** having CH_2Ph and CH_2CO_2Et instead of *t*-Bu), and (ii) the furo[*b*]pyridine derivatives **141a,b** when reacting the benzoyl-containing triafulvene **137e**.

Cyclopropenylioborates: Studies on this class[81] led to the discovery of another insertion of an isocyanide into a cyclopropene ring (Scheme 33): Compound **143** – easily prepared from **142**[82] – or its product of hydrolysis (**144**) reacted with *tert*-butyl isocyanide to give the cyclobutenimine **145** in good or reasonable yield. The molecular geometry was determined by X-ray diffraction.[83]

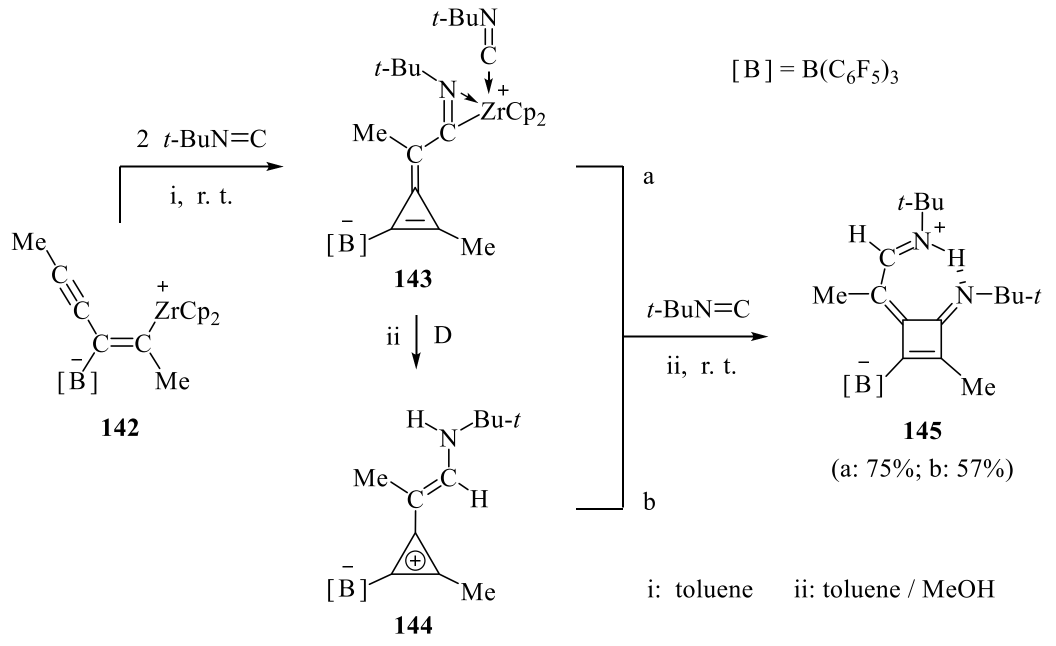
Cyclopropanedicarboxylic acid esters: A lanthanide-catalyzed insertion of aryl isocyanides into bis-acceptor activated cyclopropanes like **146** has been reported to lead directly to the cyclopentene derivatives **148** (Scheme 34). Substrates devoid of the Ar^1 ligand (which functions as an additional activator) failed to react. The conversion was viewed as proceeding *via* four-membered rings like **147**, but these species could not be observed for their high proclivity to insert an isocyanide themselves (as exemplified for Ar^1 = Ph / Ar^2 = 4-$MeOC_6H_4$).[84] Hence, the reaction of **146** parallels the behavior of oxiranes,[85] *viz.* the occurrence of double isocyanide insertion, with the failure to detect a four-membered ring,[85] which belies the quotation made in ref.[84].



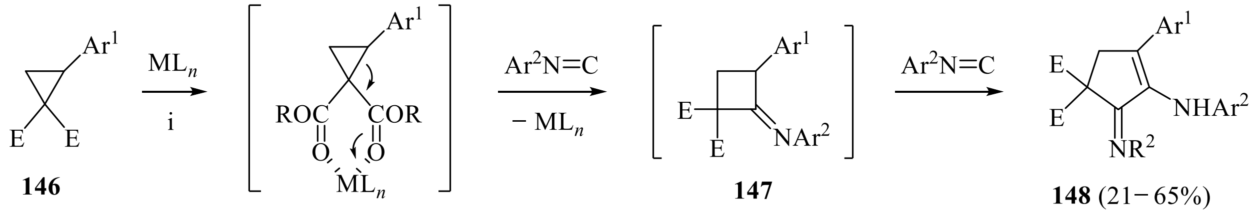
137	**138**	**140**	**141**	R1	R2	R3	Yield (%): **138**	**139**	**140**	**141**
a	**a**			COMe	COMe	c-C_6H_{11}	64			
	b			COMe	COMe	$PhCH_2$	56			
	c			COMe	COMe	EtO_2CCH_2	47			
b	**d**			COPh	COPh	c-C_6H_{11}	64			
	e			COPh	COPh	$PhCH_2$	76			
	f			COPh	COPh	$TsCH_2$	69			
c	**g**			CN	Ph	t-Bu	42			
	h			CN	Ph	c-C_6H_{11}	63			
d	**i**			CN	CN	t-Bu	0	81		
	j	**a**		CN	CN	$PhCH_2$	0		58	
	k	**b**		CN	CN	EtO_2CCH_2	0		43	
e	**l**		**a**	CN	COPh	c-C_6H_{11}	0			65
	m		**b**	CN	COPh	$PhCH_2$	0			50



Scheme 32



Scheme 33

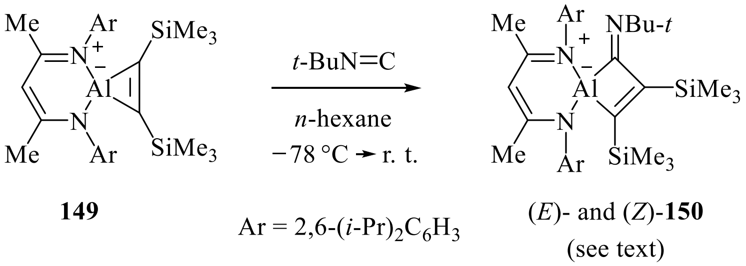


$E = CO_2Me/Et$ $ML_n = Pr(CF_3SO_3)_3$ (20 mol%) i: $ClCH_2CH_2Cl$, Δ

Ar^1 = Ph, 4-Me/$MeOC_6H_4$, 2-furyl/-thienyl Ar^2 = 4-MeO/$MeSC_6H_4$, 3-Cl-4-$MeOC_6H_3$

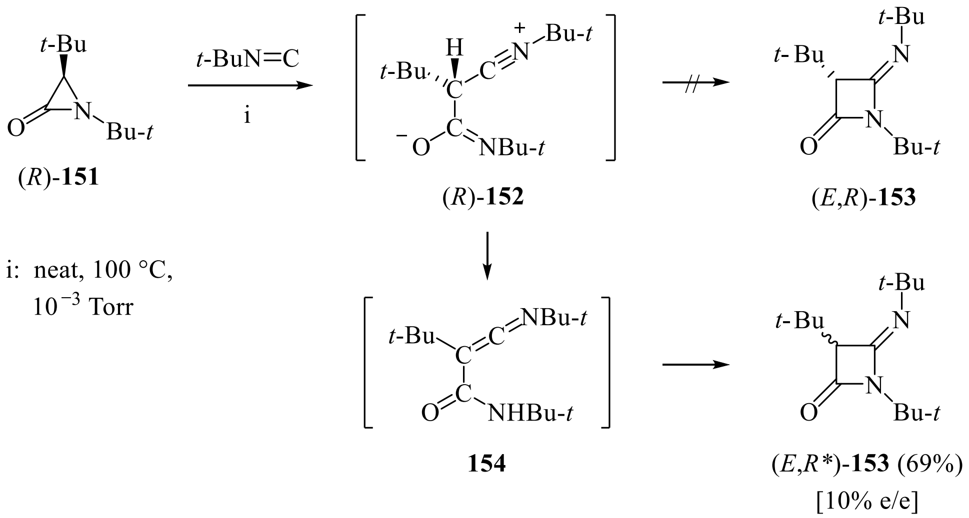
Scheme 34

1H-Aluminirene: *tert*-Butyl isocyanide was found to insert under very mild conditions into the aluminirene unit of the spiro substrate **149** to form the unique molecule **150**. Of this compound stable *E* and *Z* isomers were detected by NMR spectroscopy. Crystallization gave a solid in 57% yield that, according to X-ray diffraction, represented the *Z* configured form. It may be added by analogy that carbon monoxide transformed **149** into the corresponding aluminetimine.[86]



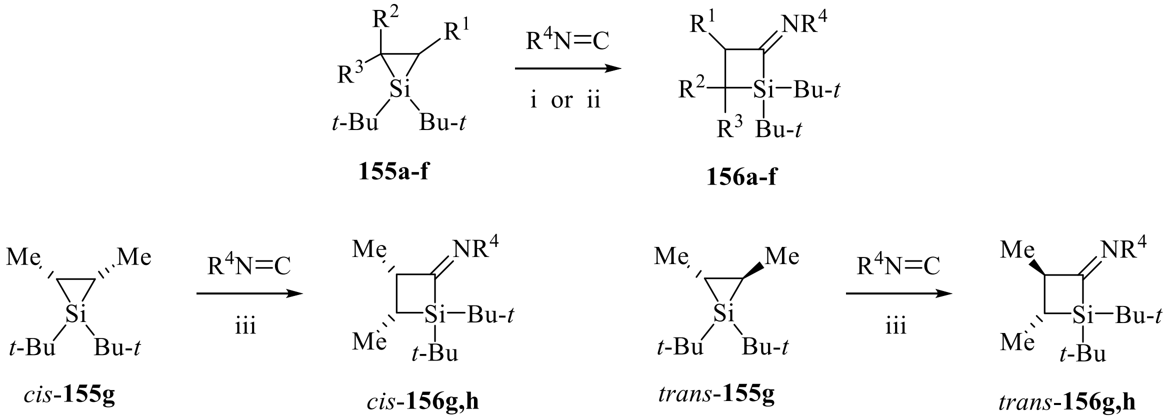
Scheme 35

α-Lactams: The conversion of this class into imino-substituted β-lactams through reaction with isocyanides is well established.[2] In a more recent work a stereochemical aspect was investigated (Scheme 36).[87] Heating the enantiomer (*R*)-**151** with *tert*-butyl isocyanide gave rise to a β-lactam like (*E,R**)-**153** of unknown absolute configuration (low enantiomeric excess), *i.e.* the stereochemical information got almost lost (if not fully). This was rationalized by considering the behavior of the zwitterionic intermediate (*R*)-**152**: this species, formed with inversion at C(3), did not cyclize directly [which must have led to (*E,R*)-**153**], but in a competing step it underwent a 1/→3/hydrogen shift to generate the ketenimine **154** which would yield racemic (*E*)-**153**.

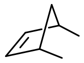


Scheme 36

Siliranes: The insertion of isocyanides into siliranes was found to affect the Si–C bond. The first known examples originated from experiments with substrates like **155a-c** and aryl isocyanides which gave the siletan-2-imines **156a-c** (Scheme 37). Of these products the derivative **156b** has been studied by X-ray diffraction, showing a practically planar four-membered ring with elongated Si–C and C–C bonds and a *Z* configured imine function.[88] Soon thereafter other authors[89] investigated regioselectivity and stereospecificity: (i) Studying the behavior of the monosubstituted siliranes **155d-f** towards *tert*-butyl isocyanide, they found that insertion occurred at the more substituted Si–C bond (→ **156d-f**), but this regioselectivity was gradually eroded as the substituent R^1 became bulkier. (ii) Reactions of *cis*- and *trans*-**155g** with *p*-tolyl and *tert*-butyl isocyanide revealed that the formation of the respective siletan-2-imines **156g,h** proceeded with stereospecific retention of configuration. As for the reactivity of these compounds, it was observed *inter alia* that both *cis*- and *trans*-**156g,h** tautomerize to 2-amino-1,4-dihydrosiletes on heating.[89]



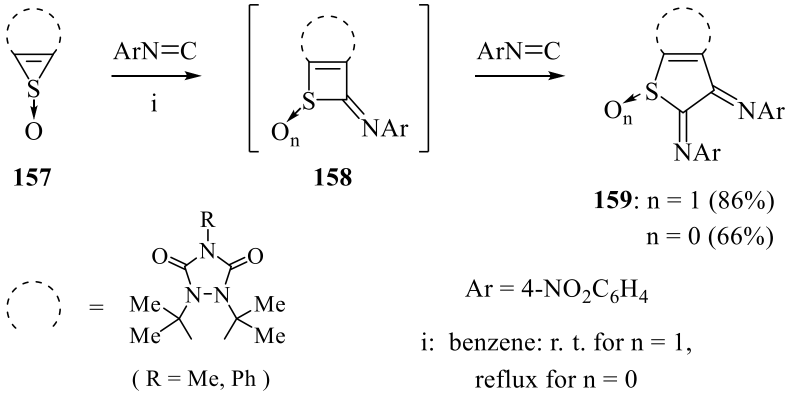
i: r. t. (solvent unreported) (for **a-c**) ii: benzene, Δ (for **d-f**) iii: benzene, r. t. (for **g**) or Δ (for **h**)

155, 156	R^1	R^2	R^3	R^4	Yield (%)	Regioselectivity[b]
a	H	Me	Me	Ph	55	
b			H	Ph	42	
c	$-[CH_2]_3-$		H	$4\text{-}NO_2C_6H_4$	34	
d	*n*-Bu	H	H	*t*-Bu	94[a]	> 95 / 5
e	*i*-Pr	H	H	*t*-Bu	98[a]	92 / 8
f	*t*-Bu	H	H	*t*-Bu	97[a]	86 / 14
cis-**g**[c]				$4\text{-}MeC_6H_4$	96	
trans-**g**[c]				$4\text{-}MeC_6H_4$	86	
cis-**h**[c]				*t*-Bu	99	
trans-**h**[c]				*t*-Bu	98	

[a] Yields refer to isolated products. [b] By ^{1}H NMR spectroscopy. [c] One diastereoisomer by ^{1}H NMR spectroscopy.

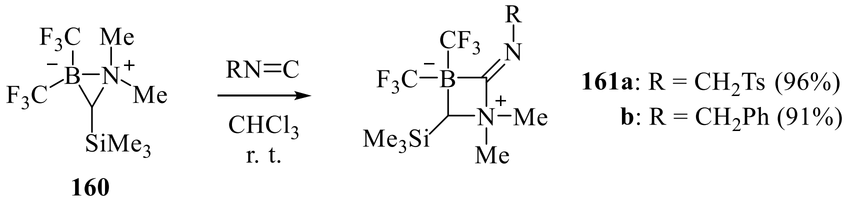
Scheme 37

Thiirene S-oxides: Isocyanide insertion into the thiirene half-ring of **157** has been accomplished with 4-nitrophenyl isocyanide (Scheme 38).[90] However, as observed with the cyclopropane derivative **146** (*cf.* Scheme 34), the reaction did not stop at the four-membered ring (**158**), but proceeded with double insertion to give a thiophenediimine **159** which, depending on the conditions, was obtained as *S*-oxide (n = 1) or deoxygenated (n = 0). Since four equivalents of the isocyanide were applied in both experiments, it is open whether **158** constitutes an elusive species.



Scheme 38

Azoniaboranuidacyclopropane: The title substrate **160** was found to react readily with tosyl and benzyl isocyanide to give in excellent yield the 1-azonia-3-boranuidacyclobutanimines **161a** and **b**, respectively (Scheme 39). The structure of **161a** has been elucidated by X-ray diffraction.[91]



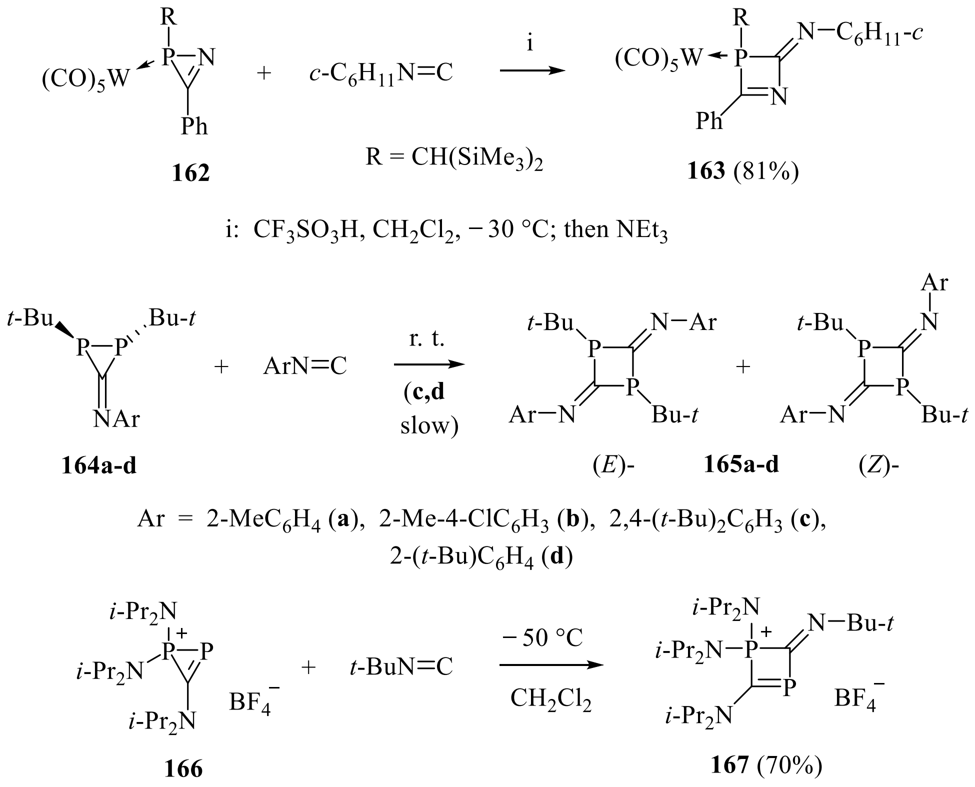
Scheme 39

Azasiliridines: For preparative reasons this class of compounds is dealt with in Section 2.2.

2H-Azaphosphirene: In the presence of a stoichiometric amount of triflic acid the azaphosphirene complex **162** underwent rapid insertion of cyclohexyl isocyanide (Scheme 40). When the reaction was quenched with triethylamine after five minutes, the dihydro-1,3-azaphosphete complex **163** was obtained in high yield. Its structural parameters have been determined by the X-ray method. Interestingly, the 3-(2-thienyl)-substituted analog of **162** did not form the corresponding product **163** (2-thienyl instead of Ph), but was converted into a 2*H*-azaphosphole derivative.[92]

Diphosphiranes, diphosphirenium: The insertion of isocyanides into the P–P bond of diphosphiranes appears as a consequence of decomposition rather than representing a preparative concept (Scheme 40).[93] Substrates like **164a-d** (made from isocyanide dichlorides and alkali diphosphides) proved partially labile, depending on the Ar substituent: The derivatives **a** and **b** having sterically less demanding ligands released isocyanide within a few hours that reacted with residual **164a,b** to give mixtures of the *E*- and *Z*-configured 1,3-diphosphetane-2,4-diimines **165a,b**; in the case of the derivatives **164c,d**, the bulkier substituents caused the respective conversion (→ **165c,d**) to occur much more slowly.[93]

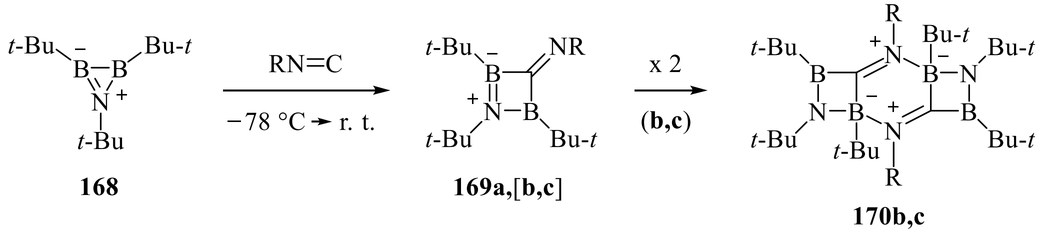
Another example of P–P bond breaking by an isocyanide was observed on treatment of the diphosphirenium salt **166** with *tert*-butyl isocyanide. As the product of insertion the 1,2-dihydro-1,3-diphosphetium derivative **167** resulted, which was characterized also by X-ray diffraction.[94]



Scheme 40

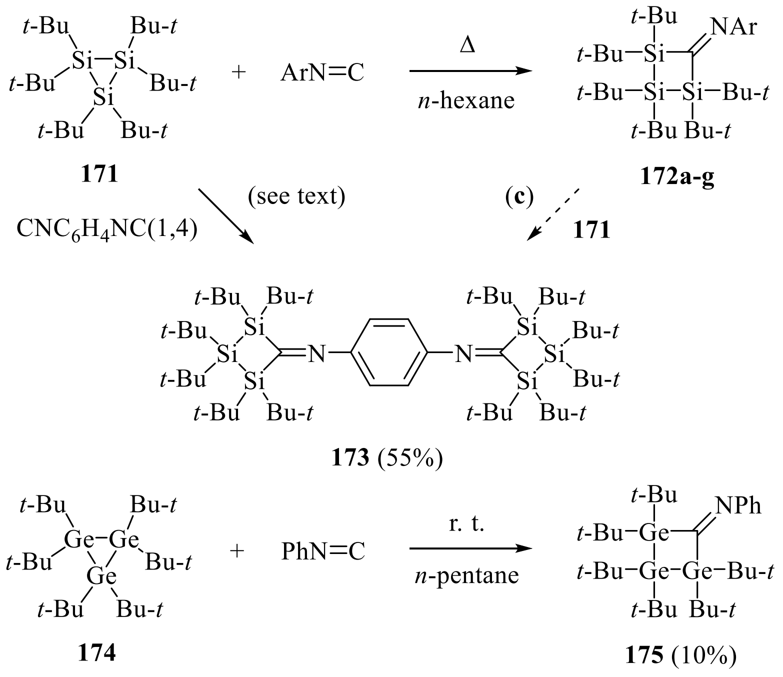
Azadiboriridine: Isocyanides were found capable of breaking the B–B bond of the azadiboridine **168** (Scheme 41). The nature of the products depends on the R ligand of the reagent: Usage of the sterically demanding 2,6-dimethylphenyl isocyanide (one equivalent only!) gave rise to the 1,2,4-azadiboretidin-3-imine **169a**, whereas the analogous products from methyl and ethyl isocyanide, *i.e.* **169b,c**, eluded isolation by undergoing a [3+3] cyclodimerization which led to the tricycles **170b,c**. Of these derivatives, **170b** has been submitted to an X-ray diffraction study.[95]

Trisilirane, trigermirane: Three-membered cycles having silicon or germanium as the sole ring atoms readily incorporate isocyanides (Scheme 42). Thus, on heating **171** with an aryl isocyanide the trisiletanimines **172a-d**[96] and **172e-g**[97] were formed. Regarding 1,4-diisocyanobenzene, less than one equivalent led to the 'bis' derivative **173** which is also accessible stepwise *via* **172c**; this product[96] as well as compound **172f**[97] has been studied by X-ray diffraction. The same kind of conversion occurred with the trigermirane **174** when treated with phenyl isocyanide (→ **175**).[98]



169, 170	R	solvent	Yield (%)
a	2,6-$Me_2C_6H_3$	CH_2Cl_2	61 (**169a**)
b	Me	pentane	89 (**170b**)
c	Et	hexane	92 (**170c**)

Scheme 41

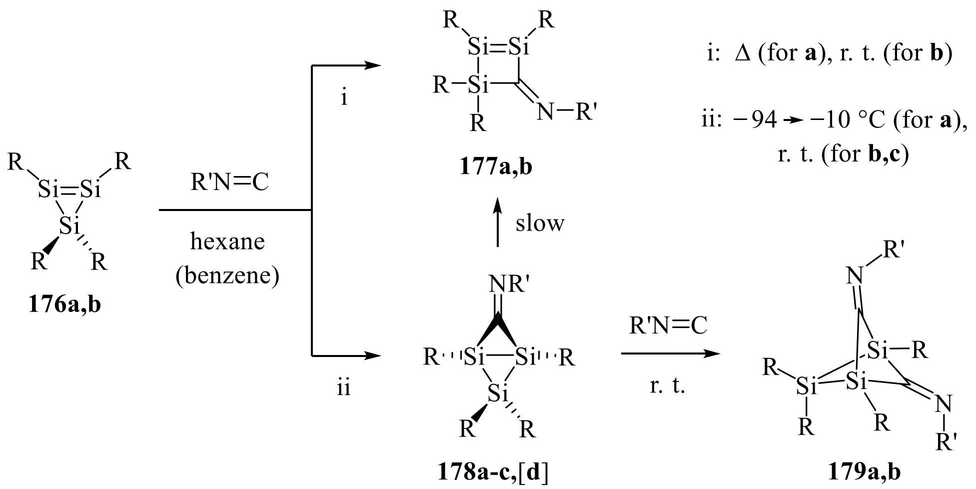


172	Ar	Yield (%)	172	Ar	Yield (%)
a	Ph	75	**e**	2,6-$Me_2C_6H_3$	18
b	4-$O_2NC_6H_4$	68	**f**	2,6-(*i*-Pr)$_2C_6H_3$	30
c	4-CNC_6H_4	61	**g**	1-naphthyl	78
d	2,4,6-$Me_3C_6H_2$	46			

Scheme 42

Trisilirenes: The behavior of this class of compounds towards isocyanides is characterized by two competing reaction modes, *i.e.* insertion into the three-membered ring and [1+2] cycloaddition across the double bond.[99] Starting from the substrates **176a,b**, the trisiletimines **177a,b** and the trisilabicyclo[1.1.1]butanes **178a-c** were prepared (Scheme 43). According to a DFT study on the models **177** and **178** having R = $SiMe_3$ / R' = *c*-C_6H_{11} and 2,6-$Me_2C_6H_3$, the derivatives **178** were found higher in energy by 2.4 and 5.1 kcal/mol, showing that they arise under kinetic control. This is best demonstrated by the reaction of **176a** with *tert*-butyl isocyanide: At room temperature a mixture of **177a** and **178a** was formed immediately; on standing, the latter component slowly rearranged to **177a**; yet, working at –94 °C, only compound **178a** was observed. – X-ray diffraction studies have been performed with **177a,b** and **178b,c** (**b**: adduct with hexane).[99]

In certain cases the isocyanide opened the Si–Si bridge in **178** to give a trisilabicyclo[1.1.1]-pentane **179**. This occurred on prolonged treatment of **176b** with two equivalents of cyclohexyl isocyanide (→ **179a**); using 2,6-dimethylphenyl isocyanide, the formation of **179b** took place even in five minutes, the intermediate **178d** being undetectable.[99]

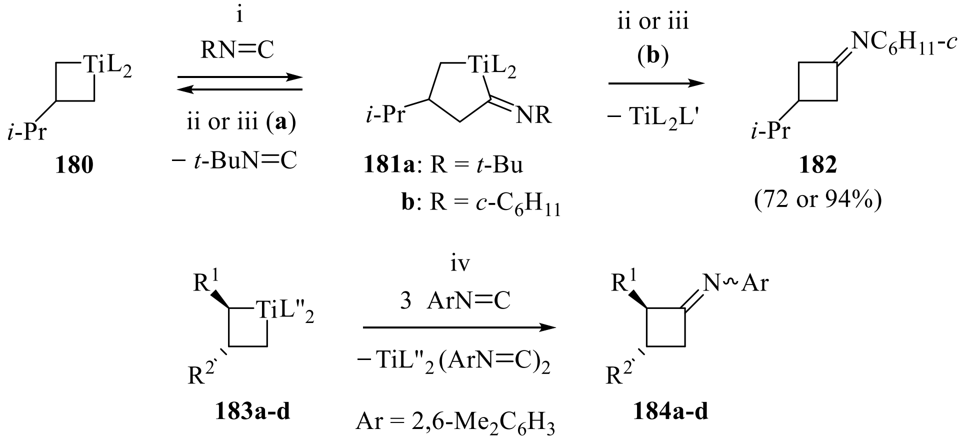


176	177	178	179	R	R'	Yield (%): 177	178	179
a	**a**	**a**		2,4,6-(*i*-Pr)$_3$C$_6$H$_2$	*t*-Bu	57	77	
		b		2,4,6-(*i*-Pr)$_3$C$_6$H$_2$	2,6-Me$_2$C$_6$H$_3$		85	
b		**c**	**a**	SiMe(*t*-Bu)$_2$	*c*-C$_6$H$_{11}$		58	81
	b	**d**	**b**	SiMe(*t*-Bu)$_2$	2,6-Me$_2$C$_6$H$_3$	48		39

Scheme 43

3.2. Migratory insertion of isocyanides into metallacycles

Titanacyclobutanes: A synthetically useful synthesis of cyclobutanimines has been developed by starting from the titanacycles **180** and **183a-d** (Scheme 44).[100] Treatment of compound **180** with *tert*-butyl and cyclohexyl isocyanide gave, respectively, the titanacyclopentanimines **181a** and **b** in ≥ 90% yield. Moderate heating of the latter induced ring contraction with demetalation to afford the cyclobutanimine **182** in 72% yield (or 94% when working in the presence of ethene).



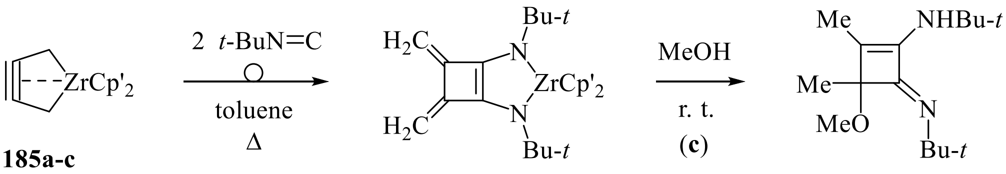
L = Cp* L' = C_2H_4 L" = 2-(dimethylamino)indenide

i: toluene, −78 °C → r. t. ii: toluene, 65 °C iii: C_2H_4 (10 psi), toluene, 65 °C
iv: THF, −35 °C → r. t.

183, 184	R^1	R^2	Yield (%)	*E* : *Z* ratio
a	Me	CH_2Ph	quant	6 : 1
b	Me	*i*-Pr	90	>99 : <1
c	Ph	CH_2Ph	quant	6 : 1
d	Ph	*i*-Pr	86	10 : 1

Scheme 44

The *tert*-butyl analog **181a**, however, reverted to the starting ring **180** when submitted to either procedure. In a second series of experiments the authors reacted the disubstituted (*trans*-configured) substrates **183a-d** with a threefold excess of 2,6-dimethylphenyl isocyanide. Here the intermediary five-membered rings were not isolated, but in a stereocontrolled manner directly converted into the cyclobutanimines **184a-d**.[100]



185a-c **186a-c** **187** (<1%)

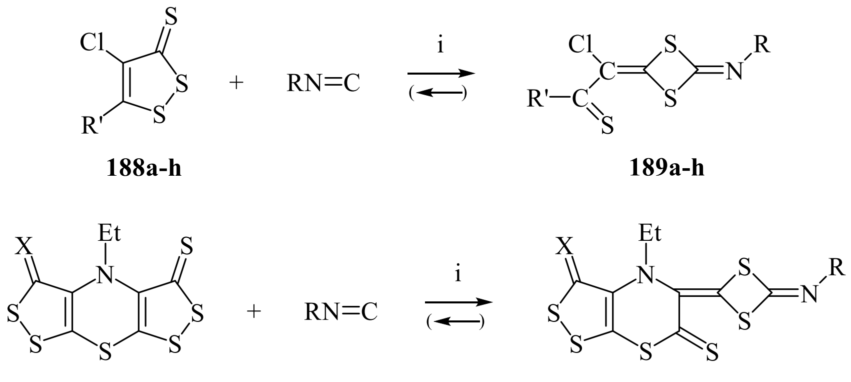
185, 186	Cp'$_2$	Yield (%)
a	Cp$_2$	85
b	[η^5-(t-Bu)C$_5$H$_4$]$_2$	44
c	Me$_2$Si(η^5-C$_5$H$_4$)$_2$	56

Scheme 45

1-Zirconacyclopent-3-ynes: Another, rather unexpected migratory insertion of an isocyanide was observed with the zirconacycles **185a-c** (Scheme 45). At slightly elevated temperature two equivalents of *tert*-butyl isocyanide were inserted into the β-Zr–C bonds, followed by a skeletal rearrangement to form the bicyclic compounds **186a-c** with a four-membered half-ring. Methanolysis of the derivative **186c** gave the monocycle **187** which, like the products **186b,c**, was studied by X-ray crystallography.[101] – The mechanism was the subject of extensive speculations, among which the assumption of an equilibrium between structure **185** and the isomeric butatriene complex placed the reaction into the neighborhood of the process **4** → **5** shown in Scheme 1.[101]

3.3. Ring transformations

3H-1,2-Dithiole-3-thiones: Under mild conditions dithiolethiones like **188a-h** were transformed into the 1,3-dithietan-2-imines **189a-h** on treatment with the respective isocyanides (Scheme 46). The reaction was shown to be reversible, especially at elevated temperature. Studying the scope, the authors found that substrates **188** lacking electron-withdrawing substituents were unreactive, nor did a reagent like benzyl isocyanide enter the process.[102] The same kind of reaction occurred with the fused systems **190a-h** to give the derivatives **191a-h**.[102,103] These examples demonstrate that a dithiolone moiety (as present in **190a-e**) is not affected and, second, that in the case of the bis(thioxodithiolo) fused thiazines **190f-h** only one of the two five-membered anellands will be involved. Moreover, replacement of the central thiazine ring in **190** with a 6π cycle like pyrrole (which on ring transformation would lose its aromaticity) resulted in total loss of reactivity.[102]



188a-h **189a-h**

190a-h **191a-h**

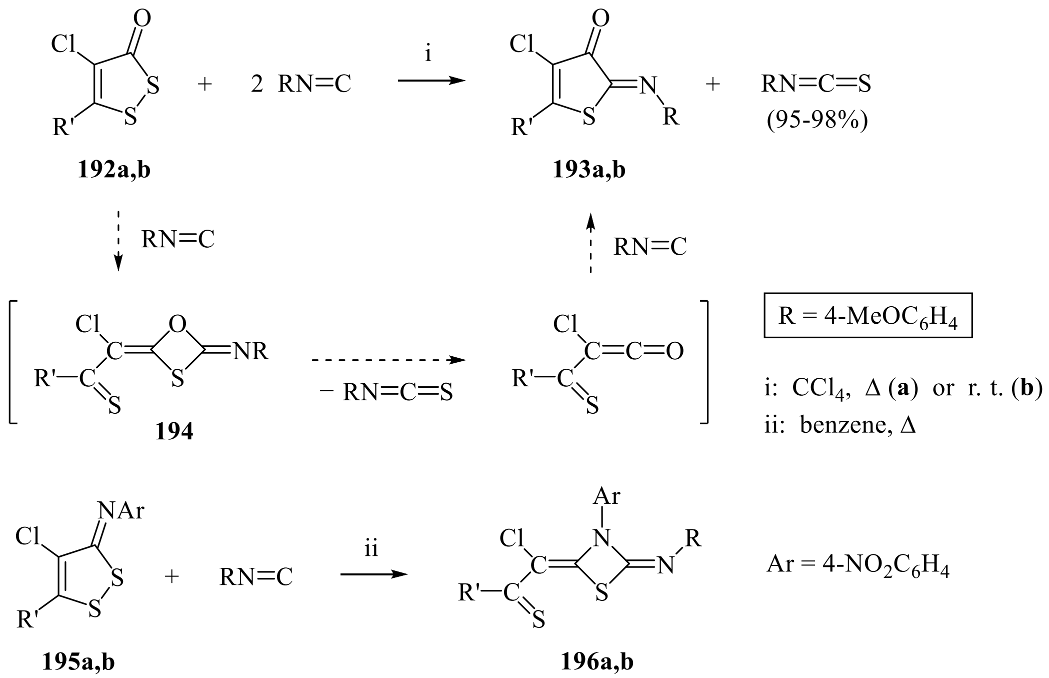
i: benzene, r. t.

188, 189	R'	R	Yield (%)	**190, 191**	X	R	Yield (%)
a / **e**	Cl / SPh	CH_2Ts	92 / 84	**a** / **f**	O / S	CH_2Ts	64 / 61
b / **f**	Cl / SPh	Ph	72 / 73	**b** / **g**	O / S	Ph	38 / 42
c / **g**	Cl / SPh	4-MeOC_6H_4	72 / 68	**c**	O	4-MeOC_6H_4	74
d / **h**	Cl / SPh	$4\text{-NO}_2C_6H_4$	85 / 84	**d**	O	$4\text{-NO}_2C_6H_4$	77
				e / **h**	O / S	CH_2CO_2Et	41 / 39

Scheme 46

3H-1,2-Dithiol-3-ones, -3-imines: Modifying the above conditions, it was found that also the hitherto unreactive 3-oxo-substituted 1,2-dithiole moiety is convertible. Experiments with both fused and monocyclic substrates revealed that a 1:2 reaction occurred to give a thiophene derivative besides an isothiocyanate, as illustrated by the process **192a,b** → **193a,b** (Scheme 47).[104,105] To rationalize this finding, the authors invoked a transient 1,3-oxathietane (**194**) which *via* [2+2] cycloreversion generates an α-thioxoketene that is ring-closed by the second isocyanide.[104]

Quite different from substrates of the type **192**, imino congeners like **195a,b** yielded isolable four-membered rings (**196a,b**) when heated with the same isocyanide.[106]



192, 193	R'	Yield (%)	**195, 196**	R'	Yield (%)
a	SPh	73	**a**	Cl	43
b	morpholino	54	**b**	PhO	47

Scheme 47

4. Conclusions

In the preceding pages we have tried to demonstrate the growing importance of isocyanides for the construction of four-membered rings. Meanwhile their diversity has gained an imposing width, as summarized below (Chart 1). Quite a number of these rings are formed with exceptional ease and are difficult to obtain by other methods. Yet, the synthetic potential of several reactions has not been fully exploited; certain transformations wait for mechanistic studies. An additional target might be the cyclic tetramerization of isocyanides to give tetraaza[4]radialenes – a pattern that is formally present in the 'four-over-one' helix (4_1) of poly(isocyanides).[107]

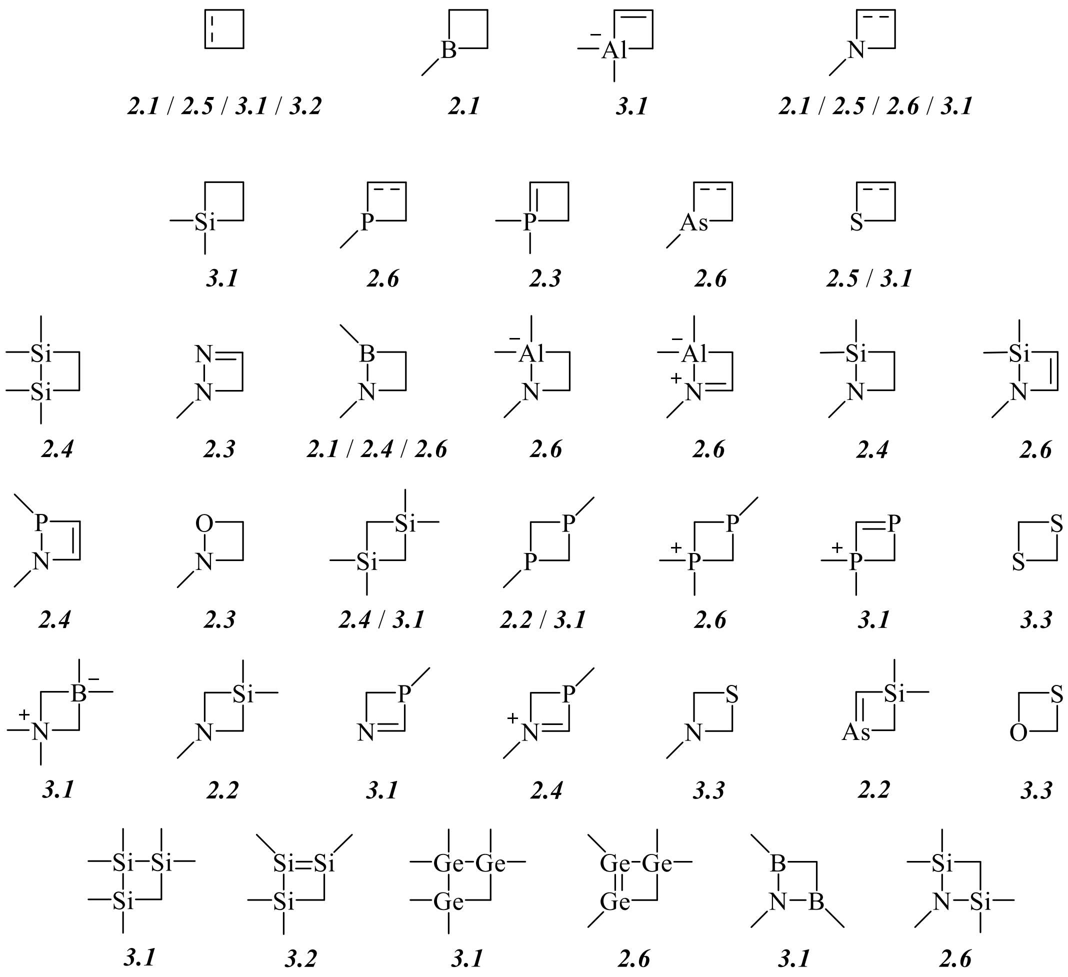


Chart 1. Ring systems from isocyanides (numerals indicate relevant sections).

References

1. Zeeh, B. *Synthesis* **1969**, 65.
   http://dx.doi.org/10.1055/s-1969-34193
2. Moderhack, D. *Synthesis* **1985**, 1083.
   http://dx.doi.org/10.1055/s-1985-31437
3. A recent monograph on isocyanides contains only a limited number of examples: Nenajdenko, V. G. Ed., *Isocyanide Chemistry*; Wiley-VCH: Weinheim, 2012.
4. Reviewed rings of this category are limited to those having main group elements.
5. Maltsev, S. S.; Mironov, M. A.; Bakulev, V. A. *Mendeleev Commun.* **2006**, *16*, 201.
   http://dx.doi.org/10.1070/MC2006v016n04ABEH002354
6. Ramakrishna, T. V. V.; Lushnikova, S.; Sharp, P. R. *Organometallics* **2002**, *21*, 5685.
   http://dx.doi.org/10.1021/om020829h

7. Fisher, R. A.; Buchwald, S. L. *Organometallics* **1990**, *9*, 871.
   http://dx.doi.org/10.1021/om00117a057
8. Lentz, D. *Z. Naturforsch.* **1992**, *47b*, 148.
9. Lentz, D. *Angew. Chem.* **1994**, *106*, 1377; *Angew. Chem. Int. Ed.* **1994**, *33*, 1315.
   http://dx.doi.org/10.1002/anie.199413151
10. Chatani, N.; Murai, S.; Hanafusa, T. *Chem. Express* **1991**, *6*, 339.
11. Adams, C. J.; Anderson, K. M.; Bartlett, I. M.; Connelly, N. G.; Orpen, A. G.; Paget, T. J.; Phetmung, H.; Smith, D. W. *J. Chem. Soc., Dalton Trans.* **2001**, 1284.
    http://dx.doi.org/10.1039/b010018h
12. Tapper, A.; Schmitz, T.; Paetzold, P. *Chem. Ber.* **1989**, *122*, 595.
    http://dx.doi.org/10.1002/cber.19891220402
13. Klöfkorn, C.; Schmidt, M.; Spaniol, T.; Wagner, T.; Costisor, O.; Paetzold, P. *Chem. Ber.* **1995**, *128*, 1037.
    http://dx.doi.org/10.1002/cber.19951281012
14. Ansorge, A.; Brauer, D. J.; Buchheim-Spiegel, S.; Bürger, H.; Hagen, T.; Pawelke, G. *J. Organomet. Chem.* **1995**, *501*, 347.
    http://dx.doi.org/10.1016/0022-328X(95)05700-Y
15. Marchand, E.; Morel, G.; Sinbandhit, S. *Eur. J. Org. Chem.* **1999**, 1729.
    http://dx.doi.org/10.1002/(SICI)1099-0690(199907)1999:7<1729::AID-EJOC1729>3.0.CO;2-S
16. Morel, G.; Marchand, E.; Malvaut, Y. *Heteroat. Chem.* **2000**, *11*, 370.
    http://dx.doi.org/10.1002/1098-1071(2000)11:5<370::AID-HC8>3.0.CO;2-J
17. Lentz, D.; Marschall, R. *Z. Anorg. Allg. Chem.* **1992**, *617*, 53.
    http://dx.doi.org/10.1002/zaac.19926170109
18. Weber, L.; Buchwald, S.; Lentz, D.; Stamm, O.; Preugschat, D.; Marschall, R. *Organometallics* **1994**, *13*, 4406.
    http://dx.doi.org/10.1021/om00023a049
19. Weber, L.; Dobbert, E.; Buchwald, S.; Stammler, H.-G.; Neumann, B. *Z. Anorg. Allg. Chem.* **1995**, *621*, 1407.
    http://dx.doi.org/10.1002/zaac.19956210821
20. Brook, A. G.; Kong, Y. K.; Saxena, A. K.; Sawyer, J. F. *Organometallics* **1988**, *7*, 2245.
    http://dx.doi.org/10.1021/om00100a033
21. Nguyen, M. T.; Vansweevelt, H.; De Neef, A.; Vanquickenborne, L. G. *J. Org. Chem.* **1994**, *59*, 8015. These authors showed in a theoretical study using HN=C and $H_2Si=CH_2$ as models that the respective [1+2] cycloadduct **28** is higher in energy than the rearranged type **29** (6.3 kcal/mol); a [2+2] cycloadduct (as hypothetical intermediate) was found to be even less stable (7.6 kcal/mol):
    http://dx.doi.org/10.1021/jo00105a016
22. Brook, A. G.; Saxena, A. K.; Sawyer, J. F. *Organometallics* **1989**, *8*, 850.
    http://dx.doi.org/10.1021/om00105a049

23. Delpon-Lacaze, G.; de Battisti, C.; Couret, C. *J. Organomet. Chem.* **1996**, *514*, 59.
http://dx.doi.org/10.1016/0022-328X(95)06036-V
24. Majumdar, M.; Huch, V.; Bejan, I.; Meltzer, A.; Scheschkewitz, D. *Angew. Chem.* **2013**, *125*, 3601; *Angew. Chem. Int. Ed.* **2013**, *52*, 3516.
http://dx.doi.org/10.1002/anie.201209281
25. Driess, M.; Pritzkow, H.; Rell, S.; Winkler, U. *Organometallics* **1996**, *15*, 1845.
http://dx.doi.org/10.1021/om9508851
26. Driess, M.; Pritzkow, H.; Sander, M. *Angew. Chem.* **1993**, *105*, 273; *Angew. Chem. Int. Ed.* **1993**, *32*, 283.
http://dx.doi.org/10.1002/anie.199302831
27. Driess, M.; Pritzkow, H. *J. Chem. Soc., Chem. Commun.* **1993**, 1585.
http://dx.doi.org/10.1039/c39930001585
28. Moderhack, D.; Lorke, M. *Heterocycles* **1987**, *26*, 1751.
http://dx.doi.org/10.3987/R-1987-07-1751
29. Moderhack, D.; Lorke, M.; Ernst, L.; Schomburg, D. *Chem. Ber.* **1994**, *127*, 1633.
http://dx.doi.org/10.1002/cber.19941270915
30. Moderhack, D.; Daoud, A.; Ernst, L.; Jones, P. G. *J. Prakt. Chem.* **2000**, *342*, 707.
http://dx.doi.org/10.1002/1521-3897(200009)342:7<707::AID-PRAC707>3.0.CO;2-2
31. Moderhack, D.; Daoud, A.; Jones, P. G. *Monatsh. Chem.* **2002**, *133*, 1165.
http://dx.doi.org/10.1007/s00706-002-0470-2
32. Moderhack, D.; Daoud, A. *J. Heterocycl. Chem.* **2003**, *40*, 625.
http://dx.doi.org/10.1002/jhet.5570400411
33. Daoud, A. Ph.D. Thesis, Technical University, Braunschweig (Germany), 2003.
34. Soeta, T.; Tamura, K.; Ukaji, Y. *Org. Lett.* **2012**, *14*, 1226.
http://dx.doi.org/10.1021/ol2034542
35. Grassot, J.-M.; Masson, G.; Zhu, J. *Angew. Chem.* **2008**, *120*, 961; *Angew. Chem. Int. Ed.* **2008**, *47*, 947.
http://dx.doi.org/10.1002/anie.200704840
36. Moderhack, D.; Lorke, M. *J. Chem. Soc., Chem. Commun.* **1977**, 831.
http://dx.doi.org/10.1039/c39770000831
37. Ruiz, J.; Gonzalo, M. P.; Vivanco, M.; Díaz, M. R.; Garzía-Granda, S. *Chem. Commun.* **2011**, *47*, 4270.
http://dx.doi.org/10.1039/c0cc05025c
38. Lentz, D.; Anibarro, M.; Preugschat, D.; Bertrand, G. *J. Fluorine Chem.* **1998**, *89*, 73.
http://dx.doi.org/10.1016/S0022-1139(98)00089-X
39. For elucidation of this mechanism, see: Amsallem, D.; Mazières, S.; Piquet-Fouré, V.; Gornitzka, H.; Baceiredo, A.; Bertrand, G. *Chem. Eur. J.* **2002**, *8*, 5306.
http://dx.doi.org/10.1002/1521-3765(20021202)8:23<5305::AID-CHEM5305>3.0.CO;2-6

40. Despagnet-Ayoub, E.; Gornitzka, H.; Bourissou, D.; Bertrand, G. *Eur. J. Org. Chem.* **2003**, 2039.
    http://dx.doi.org/10.1002/ejoc.200200657
41. Weidenbruch, M.; Brand-Roth, B.; Pohl, S.; Saak, W. *Angew. Chem.* **1990**, *102*, 93; *Angew. Chem. Int. Ed.* **1990**, *29*, 90.
    http://dx.doi.org/10.1002/anie.199000901
42. Weidenbruch, M.; Brand-Roth, B.; Pohl, S.; Saak, W. *Polyhedron* **1991**, *10*, 1147.
    http://dx.doi.org/10.1016/S0277-5387(00)86090-8
43. Weidenbruch, M.; Hamann, J.; Piel, H.; Lentz, D.; Peters, K.; von Schnering, H. G. *J. Organomet. Chem.* **1992**, *426*, 35.
    http://dx.doi.org/10.1016/0022-328X(92)83158-E
44. Weidenbruch, M. *Coord. Chem. Rev.* **1994**, *130*, 275.
    http://dx.doi.org/10.1016/0010-8545(94)80007-3
45. Xiong, Y.; Yao, S.; Driess, M. *Chem. Eur. J.* **2009**, *15*, 8542.
    http://dx.doi.org/10.1002/chem.200901337
46. Braunschweig, H.; Herbst, T.; Radacki, K.; Tate, C. W.; Vargas, A. *Chem. Commun.* **2013**, *49*, 1702.
    http://dx.doi.org/10.1039/c3cc38379b
47. Roques, C.; Mazieres, M. R.; Majoral, J.-P.; Sanchez, M. *J. Org. Chem.* **1989**, *54*, 5535.
    http://dx.doi.org/10.1021/jo00284a027
48. Mazieres, M. R.; Roques, C.; Khim, T.; Majoral, J.-P.; Wolf, R.; Sanchez, M. *Phosphorus, Sulfur, Silicon* **1990**, *49/50*, 309 (*passim*).
    http://dx.doi.org/10.1080/10426509008038967
49. Fernández, I.; Cossío, F. P.; Sierra, M. A. *Organometallics* **2007**, *26*, 3010.
    http://dx.doi.org/10.1021/om0701524
50. Aumann, R. in *Organometallics in Organic Synthesis*; de Meijere, A.; tom Dieck, H. Eds.; Springer: Berlin, Heidelberg et al., 1987; p 69.
51. Aumann, R. *Angew. Chem.* **1988**, *100*, 1512; *Angew. Chem. Int. Ed.* **1988**, *27*, 1456.
    http://dx.doi.org/10.1002/anie.198814561
52. Aumann, R.; Heinen, H.; Krüger, C. *Angew. Chem.* **1984**, *96*, 234; *Angew. Chem. Int. Ed.* **1984**, *23*, 223.
    http://dx.doi.org/10.1002/anie.198402231
53. Aumann, R.; Heinen, H. *Chem. Ber.* **1985**, *118*, 952.
    http://dx.doi.org/10.1002/cber.19851180313
54. Aumann, R.; Kuckert, E.; Heinen, H. *Angew. Chem.* **1985**, *97*, 960; *Angew. Chem. Int. Ed.* **1985**, *24*, 978. – In this paper, an ethoxy group is erroneously taken for the methoxy substituent (*cf.* refs.[50,51]).
    http://dx.doi.org/10.1002/anie.198509781
55. Aumann, R.; Krüger, C.; Goddard, R. *Chem. Ber.* **1992**, *125*, 1627.
    http://dx.doi.org/10.1002/cber.19921250718

56. Aumann, R.; Heinen, H. *Chem. Ber.* **1987**, *120*, 1297.
    http://dx.doi.org/10.1002/cber.19871200806
57. Aumann, R.; Heinen, H. *Chem. Ber.* **1988**, *121*, 1739.
    http://dx.doi.org/10.1002/cber.19881211007
58. Aumann, R.; Kuckert, E.; Krüger, C.; Angermund, K. *Angew. Chem.* **1987**, *99*, 587; *Angew. Chem. Int. Ed.* **1987**, *26*, 563.
    http://dx.doi.org/10.1002/anie.198705631
59. Aumann, R.; Heinen, H. *Chem. Ber.* **1988**, *121*, 1085.
    http://dx.doi.org/10.1002/cber.19881210611
60. Aumann, R.; Heinen, H. *Chem. Ber.* **1985**, *118*, 4186.
    http://dx.doi.org/10.1002/cber.19851181025
61. Aumann, R.; Heinen, H. *Chem. Ber.* **1986**, *119*, 2289.
    http://dx.doi.org/10.1002/cber.19861190721
62. Aumann, R.; Kuckert, E. *Chem. Ber.* **1987**, *120*, 1939.
    http://dx.doi.org/10.1002/cber.19871201205
63. Aumann, R.; Kuckert, E.; Krüger, C.; Goddard, R.; Angermund, K. *Chem. Ber.* **1988**, *121*, 1475.
    http://dx.doi.org/10.1002/cber.19881210822
64. Aumann, R.; Heinen, H. *Chem. Ber.* **1989**, *122*, 77.
    http://dx.doi.org/10.1002/cber.19891220113
65. Dyer, P.; Baceiredo, A.; Bertrand, G. *Inorg. Chem.* **1996**, *35*, 46.
    http://dx.doi.org/10.1021/ic950628o
66. Marrot, S.; Kato, T.; Cossío, F. P.; Gornitzka, H.; Baceiredo, A. *Angew. Chem.* **2006**, *118*, 7607; *Angew. Chem. Int. Ed.* **2006**, *45*, 7447.
    http://dx.doi.org/10.1002/anie.200603151
67. Junjappa, H.; Saxena, M. K.; Ramaiah, D.; Loharay, B. B.; Rath, N. P.; George, M. V. *J. Org. Chem.* **1998**, *63*, 9801.
    http://dx.doi.org/10.1021/jo981427f
68. The X-ray investigation announced in ref.[67] could not be located.
69. Cheng, F.-Y.; Sung, K.; Lee, G.-H.; Wang, Y. *J. Chin. Chem. Soc.* **2000**, *47*, 1295.
70. Ito, Y.; Suginome, M.; Murakami, M.; Shiro, M. *J. Chem. Soc., Chem. Commun.* **1989**, 1494.
    http://dx.doi.org/10.1039/c39890001494
71. Ito, Y.; Suginome, M.; Matsuura, T.; Murakami, M. *J. Am. Chem. Soc.* **1991**, *113*, 8899.
    http://dx.doi.org/10.1021/ja00023a043
72. Shapiro, P. J.; Vij, A.; Yap, G. P. A.; Rheingold, A. L. *Polyhedron* **1995**, *14*, 203.
    http://dx.doi.org/10.1016/0277-5387(94)00354-H
73. Uhl, W.; Schütz, U.; Hiller, W.; Heckel, M. *Chem. Ber.* **1994**, *127*, 1587.
    http://dx.doi.org/10.1002/cber.19941270906
74. Li, X.; Cheng, X.; Song, H.; Cui, C. *Organometallics* **2007**, *26*, 1039.
    http://dx.doi.org/10.1021/om061107j

75. Suginome, M.; Fukuda, T.; Ito, Y. *J. Organomet. Chem.* **2002**, *643/644*, 508. http://dx.doi.org/10.1016/S0022-328X(01)01321-3
76. Hitchcock, P. B.; Lappert, M. F.; Layh, M. *Angew. Chem.* **1999**, *111*, 562; *Angew. Chem. Int. Ed.* **1999**, *38*, 501. http://dx.doi.org/10.1002/(SICI)1521-3773(19990215)38:4<501::AID-ANIE501>3.0.CO;2-Z
77. Bowen, R. J.; Fernandes, M. A.; Hitchcock, P. B.; Lappert, M. F.; Layh, M. *J. Chem. Soc., Dalton Trans.* **2002**, 3253 (for correction, see p 3779). http://dx.doi.org/10.1039/b202629p
78. Iravani, E.; Neumüller, B. *Organometallics* **2005**, *24*, 842. http://dx.doi.org/10.1021/om0401197
79. Ramaker, G.; Saak, W.; Haase, D.; Weidenbruch, M. *Organometallics* **2003**, *22*, 5212. http://dx.doi.org/10.1021/om034123e
80. Eicher, T.; Stapperfenne, U. *Synthesis* **1987**, 619. http://dx.doi.org/10.1055/s-1987-28024
81. Venne-Dunker, S.; Ahlers, W.; Erker, G.; Fröhlich, R. *Eur. J. Inorg. Chem.* **2000**, 1671. http://dx.doi.org/10.1002/1099-0682(200008)2000:8<1671::AID-EJIC1671>3.0.CO;2-V
82. Temme, B.; Erker, G.; Fröhlich, R.; Grehl, M. *Angew. Chem.* **1994**, *106*, 1570; *Angew. Chem. Int. Ed.* **1994**, *33*, 1480. http://dx.doi.org/10.1002/anie.199414801
83. Ahlers, W.; Erker, G.; Fröhlich, R.; Zippel, F. *Chem. Ber./Recueil* **1997**, *130*, 1079.
84. Korotkov, V. S.; Larionov, O. V.; de Meijere, A. *Synthesis* **2006**, 3542. https://www.thieme-connect.de/DOI/DOI?10.1055/s-2006-942514
85. Bez, G.; Zhao, C.-G. *Org. Lett.* **2003**, *5*, 4991. – Paper misquoted in ref.[84] http://dx.doi.org/10.1021/ol0359618
86. Li, X.; Ni, C.; Song, H.; Cui, C. *Chem. Commun.* **2006**, 1763. http://dx.doi.org/10.1039/b601056c
87. Quast, H.; Leybach, H.; Würthwein, E.-U. *Chem. Ber.* **1992**, *125*, 1249. http://dx.doi.org/10.1002/cber.19921250535
88. Kroke, E.; Willms, S.; Weidenbruch, M.; Saak, W.; Pohl, S.; Marsmann, H. *Tetrahedron. Lett.* **1996**, *37*, 3675. http://dx.doi.org/10.1016/0040-4039(96)00650-8
89. Nguyen, P. T.; Palmer, W. S.; Woerpel, K. A. *J. Org. Chem.* **1999**, *64*, 1843. http://dx.doi.org/10.1021/jo9816257
90. Ando, W.; Hanyu, Y.; Takata, T. *J. Org. Chem.* **1986**, *51*, 2122. http://dx.doi.org/10.1021/jo00361a036
91. Brauer, D. J.; Bürger, H.; Hagen, T.; Pawelke, G. *J. Organomet. Chem.* **1994**, *484*, 107. http://dx.doi.org/10.1016/0022-328X(94)87193-0
92. Helten, H.; von Frantzius, G.; Schnakenburg, G.; Daniels, J.; Streubel, R. *Eur. J. Inorg. Chem.* **2009**, 2062. http://dx.doi.org/10.1002/ejic.200900190

93. Baudler, M.; Simon, J. *Chem. Ber.* **1987**, *120*, 421.
http://dx.doi.org/10.1002/cber.19871200327
94. Soleilhavoup, M.; Baceiredo, A.; Dahan, F.; Bertrand, G. *J. Chem. Soc., Chem. Commun.* **1994**, 337.
http://dx.doi.org/10.1039/c39940000337
95. Luckert, S.; Eversheim, E.; Müller, M.; Redenz-Stormanns, B.; Englert, U.; Paetzold, P. *Chem. Ber.* **1995**, *128*, 1029.
http://dx.doi.org/10.1002/cber.19951281011
96. Weidenbruch, M.; Hamann, J.; Pohl, S.; Saak, W. *J. Chem. Ber.* **1992**, *125*, 1043.
http://dx.doi.org/10.1002/cber.19921250510
97. Weidenbruch, M.; Hamann, J.; Peters, K.; von Schnering, H. G.; Marsmann, H. *J. Organomet. Chem.* **1992**, *441*, 185.
http://dx.doi.org/10.1016/0022-328X(92)83378-U
98. Weidenbruch, M.; Ritschl, A.; Peters, K.; von Schnering, H. G. *J. Organomet. Chem.* **1992**, *438*, 39.
http://dx.doi.org/10.1016/0022-328X(92)88004-3
99. Ohmori, Y.; Ichinohe, M.; Sekiguchi, A.; Cowley, M. J.; Huch, V.; Scheschkewitz, D. *Organometallics* **2013**, *32*, 1591.
http://dx.doi.org/10.1021/om400054u
100. Greidanus-Strom, G.; Carter, C. A. G.; Stryker, J. M. *Organometallics* **2002**, *21*, 1011.
http://dx.doi.org/10.1021/om0110080
101. Bach, M. A.; Beweries, T.; Burlakov, V. V.; Arndt, P.; Baumann, W.; Spannenberg, A.; Rosenthal, U. *Organometallics* **2007**, *26*, 4592.
http://dx.doi.org/10.1021/om700324k
102. Ogurtsov, V. A.; Karpychev, Yu. V.; Belyakov, P. A.; Nelyubina, Yu. V.; Lyssenko, K. A.; Rakitin, O. A. *Izv. Akad. Nauk, Ser. Khim.* **2009**, 422; *Russ. Chem. Bull.* **2009**, *58*, 430.
http://dx.doi.org/10.1007/s11172-010-0028-0
103. Barriga, S.; Fuertes, P.; Marcos, C. F.; Miguel, D.; Rakitin, O. A.; Rees, C. W.; Torroba, T. *J. Org. Chem.* **2001**, *66*, 5766.
http://dx.doi.org/10.1021/jo010368u
104. Ogurtsov, V. A.; Karpychev, Yu. V.; Pestravkina; D. A.; Belyakov, P. A.; Nelyubina, Yu. V.; Rakitin, O. A. *Mendeleev Commun.* **2010**, *20*, 282.
http://dx.doi.org/10.1016/j.mencom.2010.09.015
105. Ogurtsov, V. A.; Karpychev, Yu. V.; Smolentsev, A. A.; Rakitin, O. A. *Phosphorus, Sulfur, Silicon* **2011**, *186*, 1201.
http://dx.doi.org/10.1080/10426507.2010.508161
106. Ogurtsov, V. A.; Karpychev, Yu. V.; Rakitin, O. A. *Izv. Akad. Nauk, Ser. Khim.* **2012**, 677; *Russ. Chem. Bull.* **2012**, *61*, 680.
http://dx.doi.org/10.1007/s11172-012-0103-9

107. Akeroyd, N.; Nolte, R. J. M.; Rowan, A. E. In *Isocyanide Chemistry*; Nenajdenko, V. G. Ed.; Wiley-VCH: Weinheim 2012; p 551.
http://dx.doi.org/10.1002/9783527652532.ch16

Author's Biography

Dietrich Moderhack, born 1940 in Berlin, graduated from Technical University Braunschweig, Germany, where he took his PhD in 1968 (mentor: Prof. G. Zinner). From October 1974 to September 1975 he held a DFG scholarship for joining Prof. Katritzky's group at the University of East Anglia in Norwich, UK. After his Habilitation in Braunschweig (1978), he became a full Professor (1982); since October 2005, he has been retired. His major interests include triazole and tetrazole chemistry, but azapentalenes, four-membered rings with two adjacent heteroatoms and isocyanides are being looked at as well.