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Allenes from Cyclopropanes and Their Use in Organic Synthesis—Recent Developments

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Leiv K. Sydnes was born in Haugesund, Norway, in 1948. He received his M.Sc. degree at the University of Oslo in 1974 and his Ph.D. degree from the same university in 1978, both under the supervision of Professor Lars Skattebøl. After a two-year period as a postdoctoral fellow with Professor Paul de Mayo at the University of Western Ontario, Canada, he became associate professor and later full professor in organic chemistry at the University of Tromsø, Norway, the world's northernmost university. In 1993 he moved to the west coast of Norway, to take a position as professor in organic chemistry at the University of Bergen. His research interests include the development of new synthetic methods, application of photochemical reactions in synthesis, and light-induced degradation of toxic chemicals under natural conditions. He is currently President-Elect of IUPAC.

1. Introduction

Although the first allene to be characterized, 1,2-propadiene itself, was synthesized as early as 1888 by Gustavson and Demjanov,[1,2] compounds containing one or several 1,2-diene moieties remained relatively rare until the 1950s. However, from 1955 and onward several rather general methods for the synthesis of the 1,2-diene moiety were developed, and as a result the allene functionality could gradually be more easily incorporated even in rather complex molecules. Within a couple of decades a large variety of functionalized allene derivatives were readily available in considerable quantities, and during the past 40 years or so the allenyl group has developed from almost a rarity to an important and versatile synthon in organic synthesis. This development is clearly reflected in the steady flow of books and reviews dealing with the reactivity of this three-carbon unit,[3,4] and current literature reveals that the allene moiety has become an established member of the weaponry utilized in modern organic synthetic chemistry.

The first seemingly general method for the synthesis of allenes was published around 1960. Inspired by the work of Doering and LaFlamme, who obtained allenes in fair yields by treating 1,1-dihalocyclopropanes with pieces of sodium or magnesium metal at elevated temperature,[5] Moore and co-workers[6] and Skattebøl[7] discovered, almost simultaneously, that allenes were formed, generally in better yields, when the same cyclopropanes were exposed to an alkyllithium reagent at low temperature (−78 °C) instead. The mechanism of the transformation, which was coined the Doering−Moore−Skattebøl reaction, was

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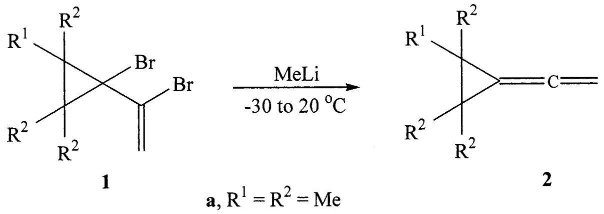
gradually uncovered and proved to involve a carbene-like intermediate (a carbenoid) or a free carbene (cyclopropylidene), formed by more or less complete collapse of the 1-halo-1-lithiocyclopropane generated when a 1,1-dihalocyclopropane undergoes lithium–halogen exchange.[8] The ring opening of various cyclopropylidenes has recently been described in detail on the basis of density functional theory and ab initio quantum-mechanical computations.[8h,8i]

The Doering–Moore–Skattebøl reaction was immediately adopted and applied by organic chemists, and over the years a large number of allenes have been synthesized according to their protocol. However, due to the immediate focus on the reaction and the considerable amount of research it generated, a number of its limitations were uncovered fairly quickly. Thus, Skattebøl discovered, for instance, that addition of methyllithium to 1,1-dibromocyclopropanes with a vinyl group attached directly to the ring furnished cyclopentadienes due to a deep-seated rearrangement (later to be called the Skattebøl rearrangement).[8d,9] It also became clear that a number of cyclopropylidenes underwent C–H insertion instead of allene formation.[7b,8d,9a,9b,10] Furthermore, it appeared that allene formation was hampered by the presence of certain substituents, which, for instance, were prone to complex with lithium, able to react with a carbenoid with a partial negative charge at the divalent carbon, or capable of intercepting intermediate cyclopropylidenes before ring opening to allene occurred.[8d,11,12] Finally, functional groups that react easily with alkyllithium reagents, such as formyl and alkoxycarbonyl groups, often complicate matters and give allenes in mediocre yields, if any at all.[8d] As a result, application of the Doering–Moore–Skattebøl reaction to incorporate an allene moiety in multifunctionalized molecules diminished as new and milder alternative allene syntheses became available.

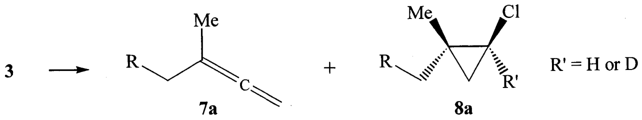
The discovery of the alkyllithium-induced conversion of *gem*-dihalocyclopropanes to allenes generated a lot of activity among experimental and theoretical chemists alike, and a large number of studies were initiated to uncover the chemical properties of halogenated and nonhalogenated cyclopropanes. All of these efforts improved the utility and extended the chemical potential of the cyclopropanes, and these improvements also included the development of alternative routes from cyclopropanes other than 1,1-dihalocyclopropanes to allene derivatives. However, as described and discussed in detail in several critical reviews,[8d,8f,8g] many of the transformations that were discovered were either impractical or so limited in scope that they were barely used and made little impact before they drifted out of focus. Cyclopropane chemistry has therefore become less important for the development and use of allene chemistry since the last timely reviews of the chemical properties of the cyclopropanes were published or prepared some 8–10 years ago.[8] Consequently, the amount of material to be covered in this contribution is rather limited, as reflected by its length.

Scheme 1



a, $R^1 = R^2 = Me$
b, $R^1 = Ph, R^2 = H$

Table 1. Treatment of 3a with 2.5 Equivalents of an Alkylmetal under Various Conditions[16]



alkyl-metal	conditions	electro-phile	products (yield, %)
BuLi	−78 °C, 5 min	H_2O	complex mixture
EtMgCl	−78 °C, 5 min	H_2O	**8a**, R′ = H (82)
EtMgCl	−78 °C, 5 min	CD_3OD	**8a**, R′ = D (77)
i-PrMgCl	−78 °C, 5 min	H_2O	**8a**, R′ = H (79)
i-PrMgCl	−78 °C, 1 h	CD_3OD	**8a**, R′ = D (80)
PhMgCl	−78 °C, 5 min	H_2O	**3a** (89) **8a**, R′ = H (trace)
PhMgCl	−78 to −60 °C, 1 h	H_2O	**3a** (71) **8a**, R′ = H (23)
PhMgCl	−78 to −50 °C, 1 h; −50 °C, 3 h	CD_3OD	**7a** (9) **8a**, R′ = D (85)
PhMgCl	0 °C, 10 min	H_2O	**7a** (82)

2. Synthesis of Allenes from Halogenated Cyclopropanes

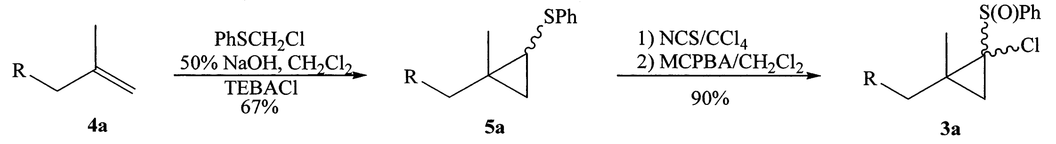
2.1. From Monohalocyclopropanes

It is well established that 1-halogeno-1-(1-haloalkenyl)cyclopropanes easily undergo elimination of halogen and form allenes (alkenylidenecyclopropanes) when treated with methyllitium.[13] In recent years the method has been used only to convert cyclopropanes **1a** and **1b** to the corresponding allenes **2a** and **2b**, which both were obtained in 98% yield when the reaction was performed at −30 to 20 °C (Scheme 1).[14]

The most recent procedure for the synthesis of allenes from cyclopropanes that are lacking a *gem*-dihalo moiety is based on Satoh's method for the preparation of magnesium carbanions by a sulfoxide–metal exchange.[15] The procedure involves addition of a Grignard reagent to a 1-chlorocyclopropyl phenyl sulfoxide (e.g. **3a**), which can easily be prepared in moderate to good overall yields from alkenes by fairly straightforward chemistry [cyclopropanation under phase-transfer conditions using triethylbenzylammonium chloride (TEBACl) as catalyst, chlorination with *N*-chlorosuccinimide (NCS), oxidation] as illustrated in Scheme 2.[16]

The conversion of 1-chlorocyclopropyl phenyl sulfoxides to the corresponding allenes **7** turned out to be sensitive to both the Grignard reagent and the temperature (Table 1).[16] Thorough studies, which included deuterium incorporation experiments and temperature variation studies, revealed that EtMgCl and i-PrMgCl were inferior to PhMgCl as reagent for

Scheme 2



R = 4-methoxybenzyl

Scheme 3

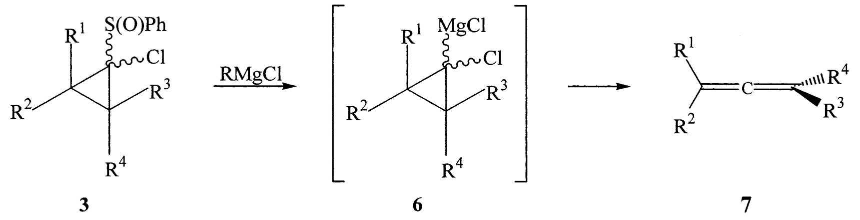
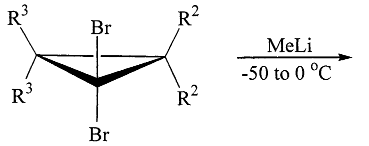


Table 2. Reaction of 1-Chloro-2*R*,3*R*′-Cyclopropyl Phenyl Sulfoxides 3 with 2.5 Equivalents of PhMgCl under Various Conditions[16]

sulfoxide **3**	reaction conditions	allene **7** (yield, %)	chloride **8** (yield, %)
3a	0 °C, 10 min	**7a** (82)	
3b[a]	−78 to −30 °C, 70 min	**7b** (25)	**8b** (47)
3b[a]	0 °C, 10 min	**7b** (82)	**8b** (trace)
3c (R = R′ = Ph)	−78 to −30 °C, 70 min	**7c** (26)	**8c** (65)
3c (R = R′ = Ph)	0 °C, 10 min	**7c** (89)	**8c** (trace)
3d (R = H, R′ = $PhCH_2CH_2$)	0 °C, 10 min	**7d** (89)	

[a] 17-Chloro-8,8-ethylenedioxy-17-(phenylsulfinyl)bicyclo[14.1.0]heptadecane.

Table 3. Conversion of 2- and 3-Substituted 1,1-Dibromocyclopropanes to the Corresponding Allenes by Reaction with MeLi



substituent at C-2 and C-3	yield of allene (%)	ref
$R^2 = CH_2SiMe_3$	only product	17a
$R^2 = Me$, $R^2 = Me$, $R^3 = CH_2SiMe_3$	only product	17a
a	only product	17a
R^2 = 1-(*tert*-butyldimethylsilyloxy)cyclopropyl, R^3 = Ph (*trans*)	92	17b
R^2 = 1-(*tert*-butyldimethylsilyloxy)cyclopropyl,, R^3 = hexyl (*trans*)	90	17b
$R^2 = R^3$ = cyclopropyl (*cis*)	82	17c

[a] 1α,2α,8α-9,9-Dibromo-2-(trimethylsilyl)bicyclo[6.1.0]nonane.

the sulfoxide−metal exchange, which gives magnesium cyclopropyl anions (**6**) as the primary products (Scheme 3). More importantly, however, it appeared that if the reaction mixture was not allowed to warm above −30 °C prior to hydrolysis, ring opening to allene did barely take place; instead, the corresponding desulfinylated cyclopropanes (**8**) were obtained in good yields. This clearly indicates that magnesium carbenoids are significantly more stable than the corresponding lithium carbenoids, which rearrange to give allenes even at −78 °C.[6,7,8d] Running the reaction above −30 °C should therefore facilitate allene formation from the magnesium carbenoids, and that turned out to be the case; when three substituted 1-chlorocyclopropyl phenyl sulfoxides were reacted with an excess of PhMgCl at 0 °C for a short time, the corresponding allenes were obtained in excellent yields (Table 2). Consequently, Satoh's method for allene preparation[16] looks very promising, although it is obvious that the Grignard reagent involved is bound to introduce significant limitations for its use when the substrates are multifunctionalized.

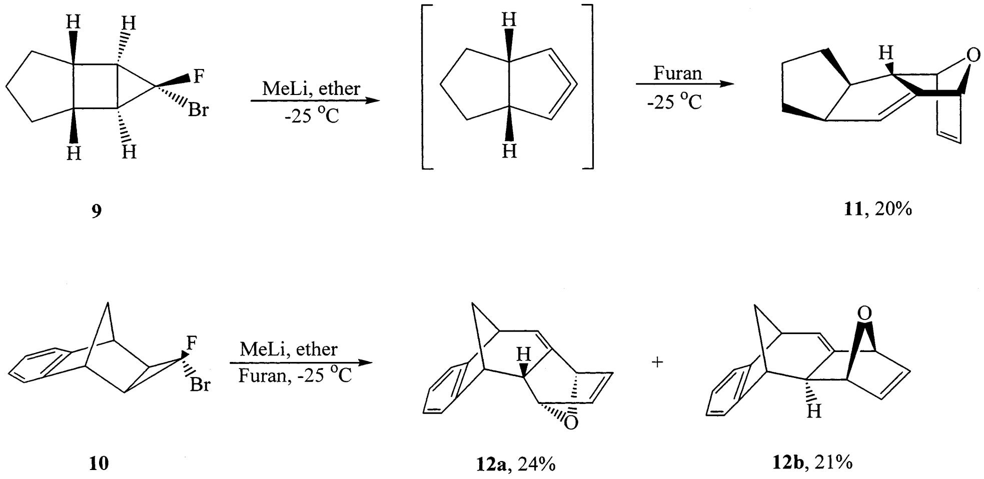
2.2. From 1,1-Dihalocyclopropanes

Few new applications of the Doering−Moore−Skattebøl procedure for allene synthesis have been reported since the last extensive reviews of the reaction.[8] Most new examples involve 1,1-dibromocyclopropanes, which are neither tetrasubstituted nor part of a bicyclic or polycyclic structure that is unable to accommodate an allene moiety without significant strain and, accordingly, should give the corresponding allenes when treated with methyllithium. The compounds appeared to behave in keeping with this prediction and gave allenes in excellent yield when treated with MeLi (Table 3).[17]

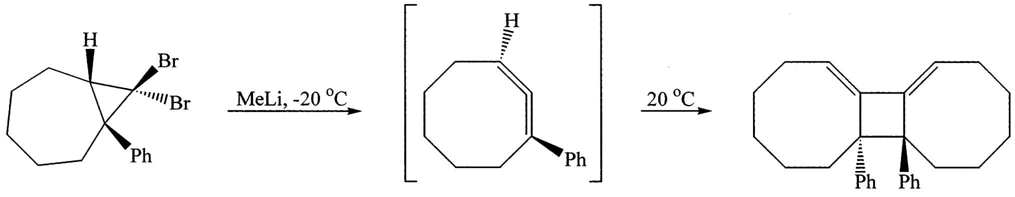
Over the years the Doering−Moore−Skattebøl reaction has been used to prepare a range of cyclic allenes that are difficult to isolate and characterize due to secondary reactions.[8,18] Recently Balci and coworkers published the conversion of two *gem*-bromofluorocyclopropanes, **9** and **10**, to the corresponding strained allenes (Scheme 4).[19] When the reactions were carried out at − 25 °C, in the presence of furan as a trapping agent, the relatively stable Diels−Alder products **11** and **12**, respectively, were obtained in fair yield (Scheme 4).[19] A noteworthy related example is the highly selective conversion of (1*R*,7*S*)-8,8-dibromo-1-phenylbicyclo[5.1.0]octane to one enantiomer of 1-phenyl-1,2-cyclooctadiene (absolute configuration unknown), which dimerizes at room temperature (Scheme 5).[20]

Among the compounds reacted are also a couple of 7,7-dibromobicyclo[4.1.0]heptane derivatives, which

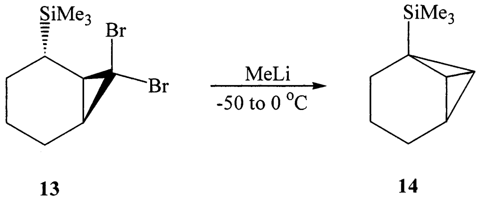
Scheme 4



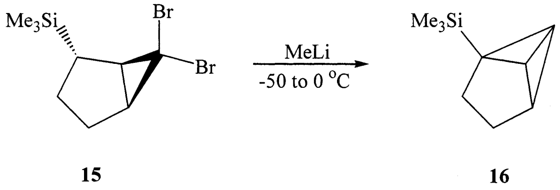
Scheme 5



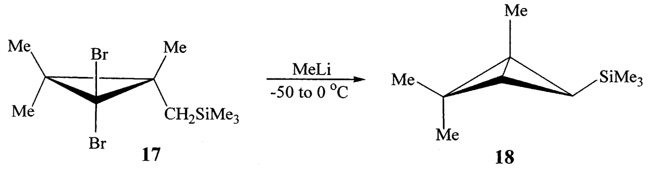
Scheme 6



Scheme 7



Scheme 8

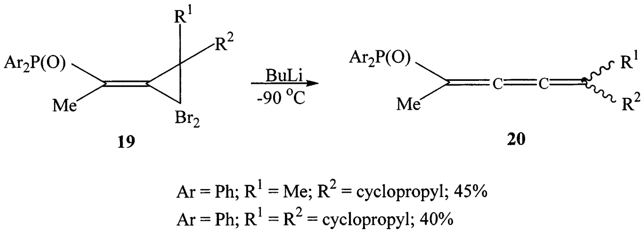


are not expected to give an allene moiety when exposed to methyllithium, but rather tricycloheptanes due to C−H insertion of an intermediate cyclopropylidene.[6a,21] Generally, C−H insertion in such systems is not regiospecific,[21] but Creary and co-workers have shown that the reaction can become so by introducing a trimethylsilyl substituent in strategic positions in the molecule.[17a] Thus, treatment of 1α,2α,6α-7,7-dibromo-2-(trimethylsilyl)bicyclo-[4.1.0]heptane (**13**) with MeLi gave one product only, 2-(trimethylsilyl)tricyclo[4.1.0.$0^{2,7}$]heptane (**14**), in 79% yield (Scheme 6). When the same reaction is performed with 7,7-dibromobicyclo[4.1.0]heptane, the reaction is not regiospecific;[21] obviously, the trimethylsilyl group causes the CH in the α position to be oriented in such a way that an effective 1,3-C−H insertion of the cyclopropylidene can occur. The same influence is clearly observed when 2*R*-substituted 6,6-dibromobicyclo[3.1.0]hexane derivatives are treated with MeLi; thus, bicyclobutane formation is not observed when R = H,[22] but when R = $SiMe_3$, 1α,2α,5α-6,6-dibromo-2-(trimethylsilyl)bicyclo[3.1.0]-hexane (**15**) gives the strained compound 1-(trimethylsilyl)tricyclo[3.1.0.$0^{2,6}$]hexane (**16**) under the same conditions (Scheme 7).[17a]

The activating influence from the trimethylsilyl group was also observed when 1,1-dibromo-2,3,3-trimethyl-2-(trimethylsilylmethyl)cyclopropane (**17**) was reacted with MeLi and 1,4,4-trimethyl-2-(trimethylsilyl)bicyclo[1.1.0]butane (**18**) was obtained (Scheme 8); thus, C−H insertion of one of the two methylene hydrogen−carbon bonds predominated quite significantly over one of the nine methyl hydrogen−carbon bonds.[17a]

Butyllithium has been used successfully to convert the *gem*-dibromocyclopropyl group in a number of 3,3-dialkyl-1,1-dibromo-2-(1-bisarylphosphinylethylidene)-cyclopropanes (**19**) to an allene moiety, but the final product after workup depends on the alkyl groups.[23] When at least one cyclopropyl group is attached to C-3 in the cyclopropane ring and both aryl groups are phenyl, no secondary reaction takes place after the allene formation is complete and the corresponding butatrienes **20** are formed (albeit in moderate yield) (Scheme 9). However, when both alkyl groups are methyl, the butatrienes are attacked at the δ carbon relative to the phosphinyl group by the cyclopropyl anion generated initially, and the only

Scheme 9



Scheme 10

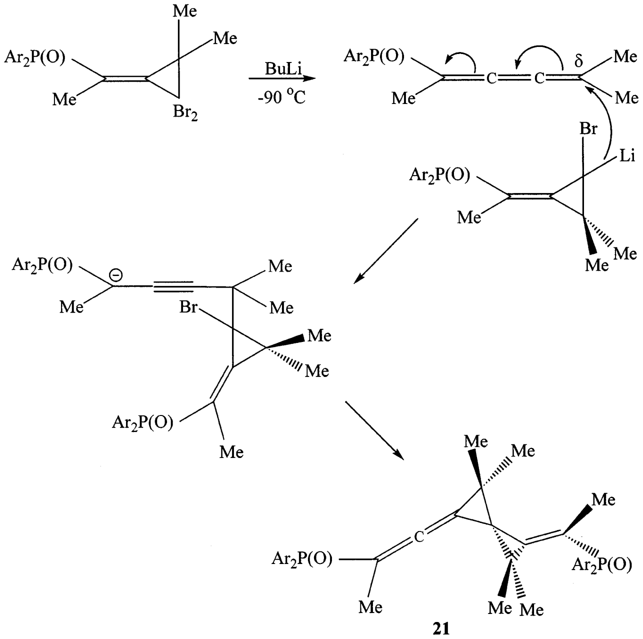


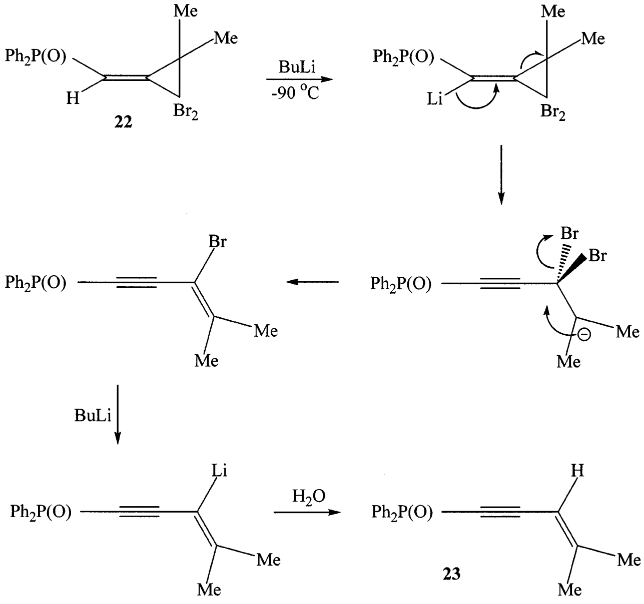
Table 4. Conversion of 19 (R^1 = R^2 = Me) to 21 by Treatment with Butyllithium[23]

Ar	yield of **21** (%)	Ar	yield of **21** (%)
phenyl	52	4-bromophenyl	41
4-chlorophenyl	68	4-*tert*-butylphenyl	58

stable products isolated are the spiropentanes **21**, each isolated as a single stereoisomer (Scheme 10).[23] The yields of the spiropentanes are surprisingly good considering the complexity of the systems involved (Table 4).

1,1-Dibromo-3,3-dimethyl-2-[(diphenylphosphinyl)-methylidene]cyclopropane (**22**) was also reacted with BuLi at low temperature, but in this case no allene formation was observed at all. Instead, enyne **23** was formed in 35% yield, conceivably because the initial attack shifts from the dibromo moiety to the relative acidic proton next to the phosphinyl group (Scheme 11).[23]

Scheme 11



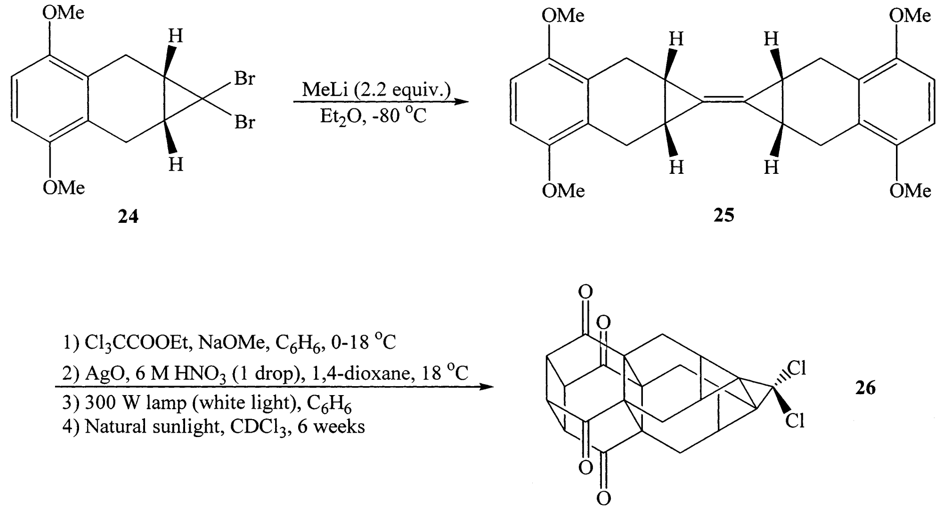
It should also be mentioned that if 1,1-dibromocyclopropanes are treated with either MeLi or BuLi at low temperature (<−78 °C) and the resulting product mixture is kept at this temperature for a period of time, the stability of the corresponding 1-bromo-1-lithiocyclopropanes formed initially may increase enough to favor other reactions at the expense of allene formation.[8d−g] This has been utilized by Banwell and co-workers to convert the tricyclic *gem*-dibromocyclopropane **24** to the *syn*-cyclopropylidene dimer **25**, which, after addition of dichlorocarbene, oxidation, and photolysis, affords the tube-like compound **26** (Scheme 12).[24] The yield of **25** was rather low (only 11%) due to formation of a number of other products, including its *anti* analogue.

Furthermore, if *gem*-dibromocyclopropanes are treated with an alkyllithium reagent at −95 °C or below and copper(II) chloride is added before or after the lithium reagent has been introduced, a formal carbene dimerization generally becomes much more efficient and may in a number of cases completely predominate.[25] This is, for instance, the case when 2-benzyl-1,1-dibromocyclopropane (**27**) is reacted with BuLi at −95 °C to afford 2,2′-dibenzyl-1,1′-bi(cyclopropylidene) (**28**) in 87% yield as a mixture of all possible stereoisomers (Scheme 13).[25a]

It should also be mentioned that the Doering−Moore−Skattebøl method has been used to convert 1,1-dibromo-2-phenyl-3,3-dimethylcyclopropane (**29**) to 3,3-dimethyl-2-phenyl-1-trimethylsilylcyclopropene (**30**),[26] which gives an allene when irradiated under the right conditions (see section 2.3). The synthesis is summarized in Scheme 14.

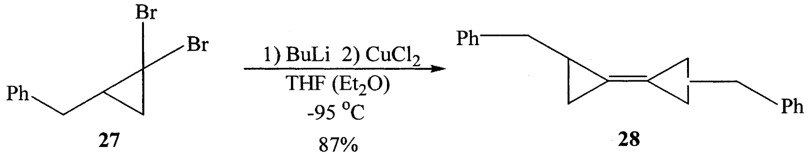
It is well established that *gem*-dibromocyclopropanes react with Grignard reagents and as a rule give an isomeric mixture of the corresponding monobromocyclopropanes in fairly good yield.[8f,8g,27] It was therefore surprising when Oshima and co-workers reported that the reaction of 1,1-dibromo-2-hexylcyclopropane with butylmagnesium bromide affords 1,2-nonadiene[28a] and that other *gem*-dibromocyclopropanes react with lithium tributylmagnesate and give the corresponding allene as byproducts.[28b] On this basis Baird and co-workers re-examined the reaction of such cyclopropanes with Grignard reagents and found that under optimum conditions, *gem*-dibromocyclopropanes which yield cyclopropylidenes that can easily undergo ring opening, furnish the corresponding allenes in very high yield.[29] The best results were obtained when the reaction was performed at room temperature. At lower temperature stable 1-bromo-1-(bromomagnesio)cyclopropanes

Scheme 12



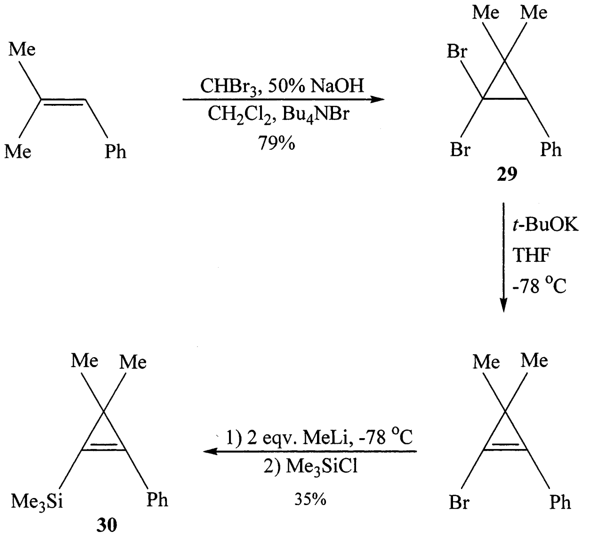
24 **25** **26**

Scheme 13



27 **28**

Scheme 14



29 **30**

Table 5. Reaction of 32 with Different Grignard Reagents[a] in THF under Identical Conditions at Ambient Temperature[29]

Grignard reagent	product distribution[b]		
	31	**32**	**33**
EtMgBr	3	97	tr
EtMgCl		81	18
i-PrMgBr		98	1
t-BuMgCl	33	16	48
$PhCH_2MgBr$	16	82	tr
PhMgBr	92	1	2
MeMgCl	87	11	2

[a] An excess of the Grignard reagent was used, 2.0 mol equiv of *t*-BuMgCl, 1.5 mol equiv of the others. tr, trace. [b] Product distribution was determined by GLC analysis.

Table 6. Preparation of Allenes 32 from *gem*-Dibromocyclopropanes 31 with Ethylmagnesium Bromide in THF at Ambient Temperature[29]

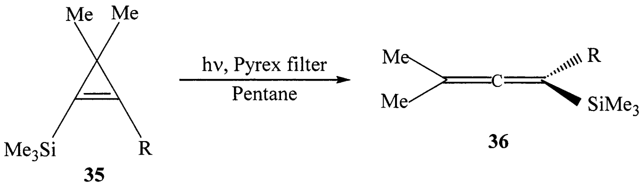
starting material	amount of Grignard reagent (mol equiv)	isolated yield of **32** (%)
31a	1.7	96
31b	1.3	96
31c	1.3	92
31d	2.0	93
31e	1.7	91

are formed and may be trapped by a number of electrophiles, in accordance with the observation that magnesium carbenoids are significantly more stable than the corresponding lithium carbenoids (see section 2.1). Thorough studies of the conversion of 1,1-dibromo-2-methyl-2-phenylcyclopropane (**31**) to 3-phenyl-1,2-butadiene (**32**), which usually gave a *cis*/*trans* mixture of 1-bromo-2-methyl-2-phenylcyclopropane (**33**) as byproduct, revealed that ethylmagnesium bromide was the preferred reagent (Table 5) and that 1.3–2.0 mol equiv of the reagent were required to achieve complete conversion.[29] Other *gem*-dibromocyclopropanes were reacted under the same conditions and, indeed, the corresponding allenes were obtained in excellent yields (Table 6).[29] Given the advantages of ethylmagnesium bromide over any alkyllithium reagent with respect to preparation, stability, and reaction conditions, it is obvious that Baird's method may offer significant benefits in allene synthesis.

2.3. From 1,1,2-Trihalocyclopropanes

It is well established that 1,1,2-trihalocyclopropanes do not give allenes but undergo dehalogenation and furnish 1-halocyclopropenes when treated with

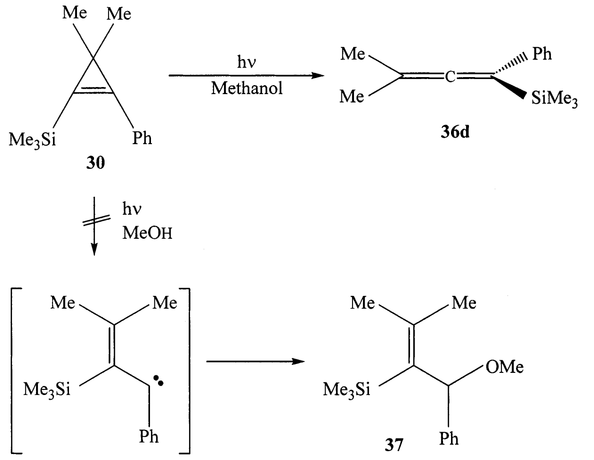
Scheme 15



35 **36**

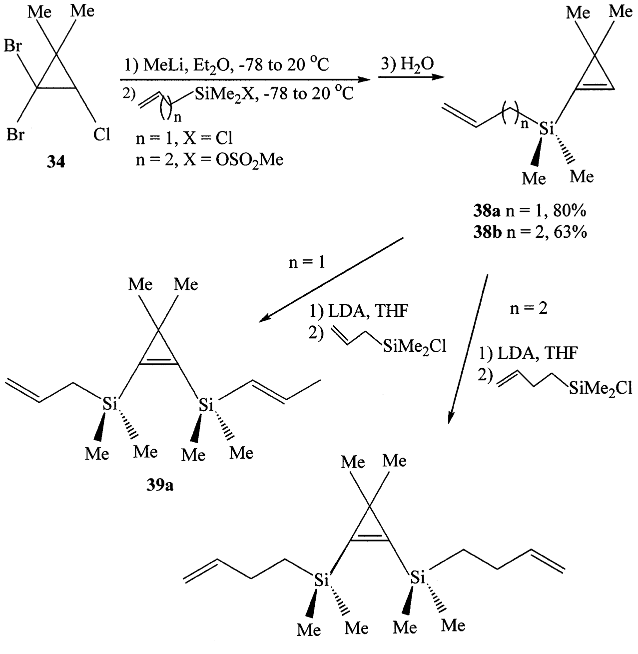
a, R = C(O)Et **a**, 85%
b, R = C(Et)=CH_2 **b**, 65%
c, R = C(O)*t*-Bu **c**, 76%

Scheme 16



30 **36d** **37**

Scheme 17



34

38a n = 1, 80%
38b n = 2, 63%

39a **39b**

alkyllithium.[30] Such cyclopropenes are rather unstable,[30b,30c,30e] but when an additional equivalent of alkyllithium is added, the corresponding 1-lithiocyclopropenes may be formed and, if formed, can be electrophilically substituted by means of several reagents to give synthetically useful compounds. One useful electrophilic reagent is trimethylsilyl chloride, which furnishes the corresponding 1-(trimethylsilyl)cyclopropenes that are known to rearrange to allenylsilanes upon direct photolysis.[31]

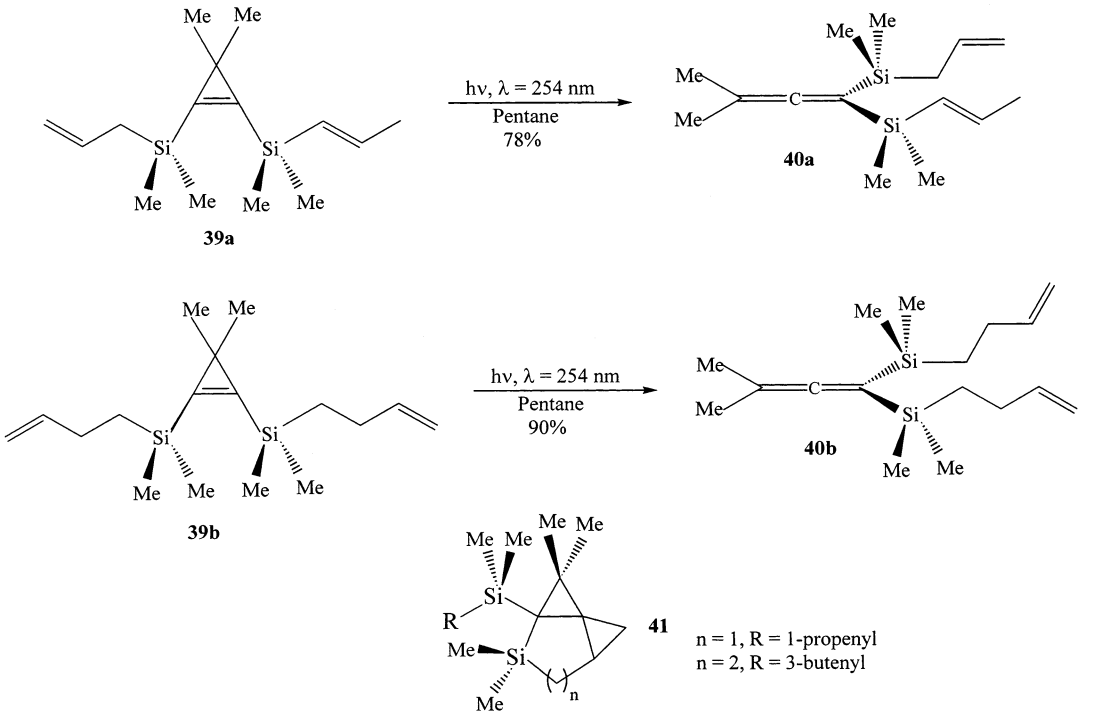
This strategy has recently been used to prepare a selection of variously substituted allenes with 1,1-dibromo-2-chloro-3,3-dimethylcyclopropane (**34**) as starting material. Kirms and co-workers treated this cyclopropane with 2 equiv of methyllithium followed by chlorotrimethylsilane and obtained 1-trimethylsilyl-3,3-dimethylcyclopropene, which was used to make cyclopropenes **35a**−**c** for subsequent photolysis.[26] When these cyclopropenes were dissolved in pentane and exposed to Pyrex-filtered light from a medium-pressure mercury lamp, they were efficiently consumed and gave in each case an allenylsilane (**36**) as the main product in good yield (Scheme 15). Compound **30** reacted in an analogous fashion and gave the corresponding allene in 80% yield.[26]

Generally it is believed that cyclopropenes rearrange via a vinylcarbene intermediate under both photolytic and thermal conditions.[32] However, when cyclopropene **30** was photolyzed in methanol instead of pentane to trap the conceivable transient vinylcarbene and isolate the expected methoxylated derivative **37**, none of the product was detected; the only compound isolated and characterized was 3-methyl-1-phenyl-1-(trimethylsilyl)buta-1,2-diene (**36d**), which was obtained in quantitative yield (Scheme 16).[26] It is therefore reasonable to believe that 1-(trimethylsilyl)cyclopropene derivatives are converted to allenes via one or several noncarbenoid pathways.

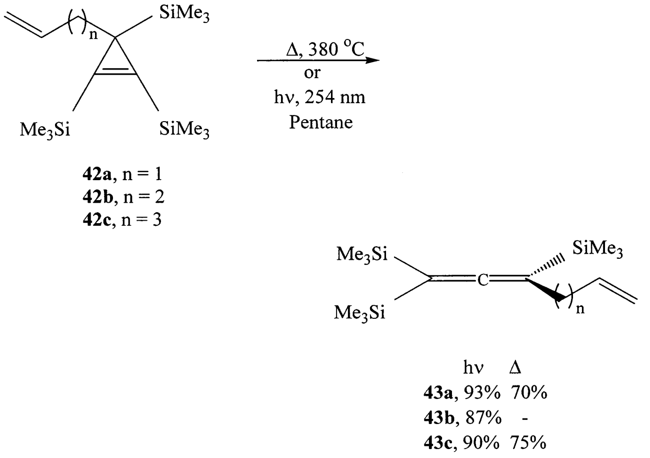
Cyclopropane **34** was also used by de Meijere and co-workers to prepare two 1,2-disilylated 3,3-dimethylcyclopropenes for mechanistic studies;[33] the syntheses are shown in Scheme 17. Treatment with 2 equiv of MeLi followed by the addition of allylchlorodimethylsilane or but-3-enyl(methylsulfonyloxy)dimethylsilane gave the monosilylated cyclopropenes **38a** and **38b**. Both compounds were then deprotonated with lithium diisopropylamide (LDA) at −78 to 20 °C and subsequently substituted with the appropriate alkenylchlorodimethylsilane reagents in the same temperature range to give the corresponding bisilylated cyclopropenes **39a** and **39b** in 45 and 40% yields, respectively. (The 1-propenyl group attached to one of the silicon atoms in **39a** was formed from an allyl moiety by a base-catalyzed double-bond shift.[33]) Subsequent irradiation of both compounds in pentane with a low-pressure mercury lamp (λ = 254 nm) resulted in complete conversion of both cyclopropenes to the corresponding allenes **40a** and **40b** (Scheme 18).[33] In neither case were even traces of the expected[34] trapping product **41** detected, which supports the theory that 1-silylated cyclopropenes are converted to allenes via noncarbenoid pathways.

It should also be mentioned that de Meijere and co-workers have synthesized three 3-alkenyl-1,2,3-tris(trimethylsilyl)cyclopropenes (**42**) [from tris(trimethylsilyl)cyclopropenylium hexachloroantimonate[33]], which were photolyzed (with light from a low-pressure mercury lamp) and thermolyzed separately.[33] In all experiments except one the corresponding allene (**43**) was formed in good or excellent yield (Scheme 19); the exception was 3-(but-3-enyl)-1,2,3-tris(trimethylsilyl)cyclopropene (**42b**), which furnished norcar-3-ene derivative **44** when heated in toluene at 210 °C (Scheme 20). The only reasonable mechanism to account for the formation of **44** would be an inter-

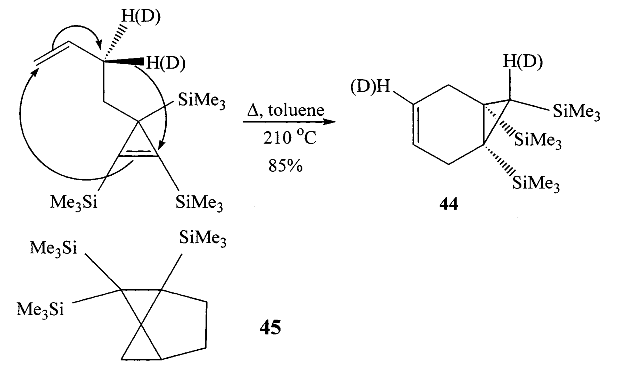
Scheme 18



Scheme 19



Scheme 20



molecular ene reaction, which proceeds as indicated in Scheme 20 and the involvement of which is supported by the absence of spiropentane **45**. The spiropentane would most likely have been formed if a cyclopropylidene intermediate had been involved.[9a,34]

3. Allenes from Nonhalogenated Cyclopropanes with No Allene Moiety

The literature contains a number of examples of modified cyclopropane reactivity caused by substituents attached directly to the ring. One group that can induce reactivity changes is the ethynyl group, particularly in combination with other substituents; ethynylcyclopropanes have therefore gained interest as synthetic building blocks over the past decade or so.[35] One such derivative, *trans*-1-ethoxy-2-ethynylcyclopropane (**46**),[36] appears to be an excellent starting material for the synthesis of the 3,4-pentadienal moiety with a protected aldehyde functionality.[37] The reagent facilitating this transformation is the binuclear ruthenium precatalyst $[Ru(O_2CH)(CO)_2(PPh_3)]_2$, which is known to promote selective Markovnikov-type addition of carboxylic acids to terminal alkynes, including cyclopropylethyne, without rearrangements.[38]

When a mixture of **46** and a carboxylic acid in benzene is treated with this ruthenium complex at elevated temperature (70−75 °C), regioselective ring opening of the cyclopropane ring takes place to furnish the corresponding 1-acyloxy-1-ethoxypenta-3,4-diene (**47**), a derivative of penta-3,4-dienal, which suffers polymerization easily unless the aldehyde group is protected. The yield is generally >90% when the acid exhibits minimal steric bulk, but with sterically more demanding compounds, such as pivalic acid, concomitant formation of the corresponding *trans*-1-(1-acyloxyethenyl)-2-ethoxycyclopropane (**48**) generally takes place (Scheme 21) (Table 7).[37]

Two interesting observations are relevant for an understanding of the mechanism of this formal 1,4-addition of carboxylic acids to **46**.[31] First, enol benzoate **48f** is unchanged after extensive heating in the presence of the ruthenium catalyst; consequently,

Scheme 21

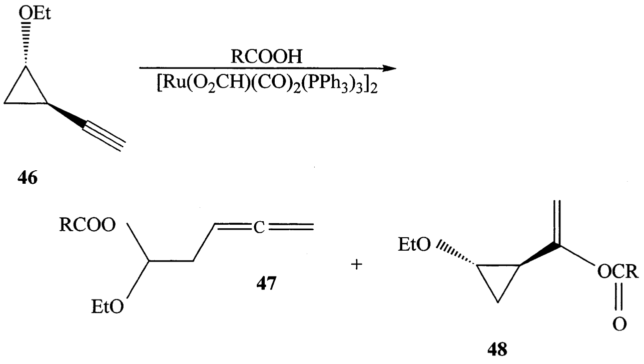
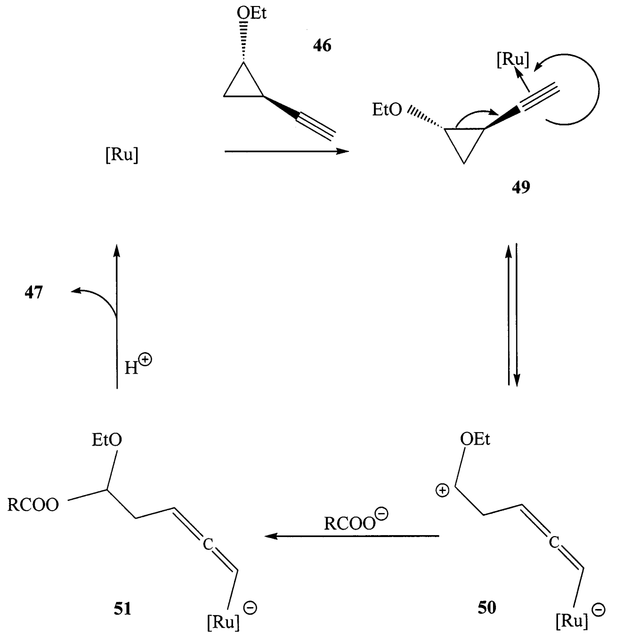


Table 7. Conversion of 46, with $[Ru(O_2CH)(CO)_2(PPh_3)]_2$ and RCOOH in Benzene at 70−75 °C, to 47 and 48[37]

R	amount of catalyst (mol %)	reaction time (h)	yield of **47** (%)	yield of **48** (%)
Me	1.0	3	**a**; 96	
Bu	0.2	6	**b**; 84	
CH_2=$CH(CH_2)_8$	0.4	6	**c**; 92	
cyclopropyl	0.4	4	**d**; 93	
t-Bu	0.4	6	**e**; 62	**e**; 29
Ph	0.4	6	**f**; 58	**f**; 27
5-methyl-2-thienyl	0.4	6	**g**; 53	**g**; 21
2-iodophenyl	0.4	6	**h**; 68	**h**; 18
2-acetylphenyl	0.4	6	**i**; 58	**i**; 10

Scheme 22



compounds **47** do not result from a rearrangement of **48** once the latter are formed. Second, experiments proved that **46** is unreactive when treated with the precatalyst at elevated temperature *in the absence* of a carboxylic acid. On this basis the reaction has been described as a multistep process starting with electrophilic attack of the ruthenium complex on the triple bond to give η^2-coordination compound **49** (Scheme 22). Because the allene formation is strongly associated with the ethoxy group, it is conceivable that the decreased electron density at the triple bond, caused by the metal coordination, favors the opening of the ring to give the zwitterionic intermediate **50**. The positive charge, stabilized by the oxygen atom, is then attacked by the carboxylate to give the σ-allenylruthenium complex **51**, which affords **47** upon protonolysis.

An ethynylcyclopropane moiety is also believed to be involved when 7-ethynyl-1,3,5-cycloheptatrienes (**52**) rearrange to the corresponding arylallenes (**53**) at 60 °C in THF containing trifluoroacetic acid (TFA) (Scheme 23).[39] Valence tautomerism converts the cycloheptatriene to the norcaradiene form, and subsequent protonation of the triple bond gives a vinyl cation, which facilitates cleavage of the cyclopropane ring and, eventually, formation of **53**. Both **52a** and **52b** were formed in quantitative yield, but the latter reacted >300 times more rapidly than the former, probably because bulky substituents shift the cycloheptatriene−norcaradiene equilibrium toward norcaradiene.[39]

4. Allenes from Cyclopropanes with an Allene Moiety

Certain allenes, particularly aryl-substituted ones, have also been prepared by photolysis and thermolysis of 1-ethenylidenecyclopropanes substituted at the 2- and 3-positions of the three-membered ring and at the 2′-carbon of the ethenylidene moiety. Such cyclopropanes, which can be prepared according to various procedures,[40] including the reaction of 1,1-dibromocyclopropanes with NaOH under phase-transfer conditions in the presence of an alkene and tetrabutylammonium hydrogensulfate,[41] may be converted to other allenes in reactions that may or may not involve cleavage of the cyclopropane ring.

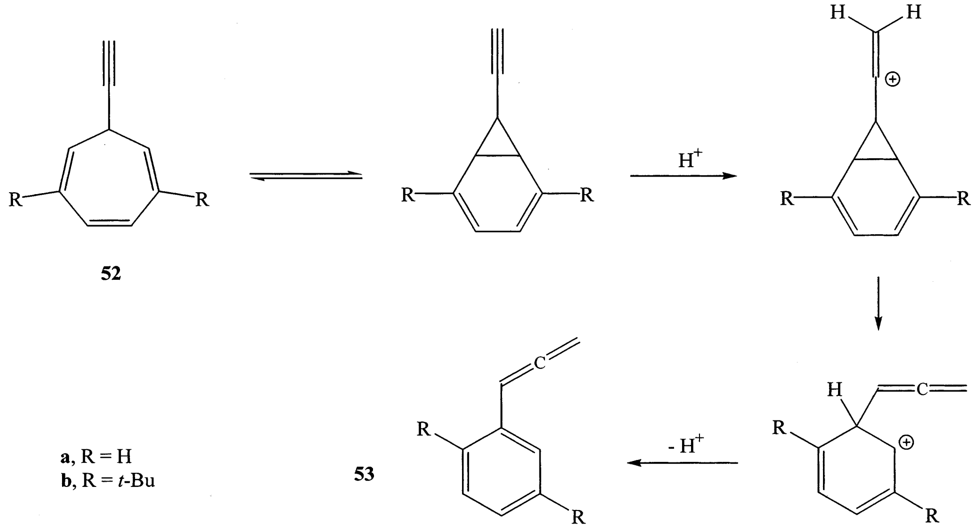
4.1. With Temporary Cleavage of the Cyclopropane Ring

Some 1-(2′,2′-diarylethenylidene)-*cis*-2,3-dimethylcyclopropanes (**54a**−**e**) and 1-(2′-methyl-2′-phenylethenylidene)-*cis*-2,3-dimethylcyclopropane (**54f**) have been converted to the corresponding *trans* isomers **55** by irradiation under various conditions.[42,43] Irrespective of the reaction conditions during the photolysis, the isomerization is in no case complete, because the *trans* isomers also react and regenerate the corresponding *cis* isomers (Scheme 24). Consequently, a reaction mixture with a *cis*/*trans* ratio that does not change, a so-called photostationary state (PSS), is achieved after some time. The time it takes to reach the PSS is sensitive to the structure of the compound and the mode by which the excited state of the ethenylidenecyclopropane moiety is achieved.

Direct irradiation[42] gave in most cases a PSS mixture close to 1:1 in both benzene and more polar solvents. Furthermore, the photoisomerization was not quenched by typical triplet quenchers such as oxygen, isoprene, and cyclohexa-1,3-diene; this is indicative of a singlet mechanism for the process.

The photoisomerization occurs even more quickly in the presence of triplet sensitizers such as acetophenone, benzophenone, and Michler's ketone (MK) to give a *cis*/*trans* PSS mixture close to 3:7 (Table 8).[42] Pyrene, however, did not sensitize the

Scheme 23



Scheme 24

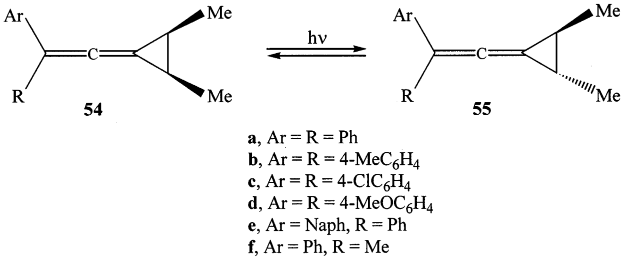


Table 8. Direct and Sensitized *cis*–*trans* Isomerization of 54 and 55[42]

substrate	direct irradiation (**54**:**55** ratio on PSS)	sensitization (**54**:**55** ratio on PSS)	sensitizer
54a	50:50	30:70	Michler's ketone
55a	50:50	30:70	Michler's ketone
54a		30:70	acetophenone
54a		27:73	benzophenone
54b	50:50	27:73	Michler's ketone
54c	54:46	27:73	Michler's ketone
54d	46:54	29:71	Michler's ketone
54e	25:75	27:73	Michler's ketone
55f	45:55	25:75	Michler's ketone

reaction; it is therefore conclusive that the triplet energy of the ethenylidenecyclopropanes is larger than that of pyrene (203 kJ/mol).[42] It is also interesting to note that the ratios obtained after PSS has been achieved in both direct and triplet-sensitized irradiations do not depend on the substituents on the phenyl ring, only on the multiplicity of the excited state.

The *cis/trans* photoisomerization can also be performed by 9,10-dicyanoanthracene (DCA) sensitization, which involves an electron-transfer chain process.[42,43] The isomerization of 1-[2′,2′-bis(4-methoxyphenyl)ethenylidene]-*cis*-2,3-dimethylcyclopropane (**54d**) has been studied particularly thoroughly, and the studies revealed that its efficiency is very dependent on the solvent used as well as additives utilized to accelerate the reactions. The effects are clear from the data compiled in Tables 9 and 10. Photolyses performed with $Mg(ClO_4)_2$ added were particularly efficient, as reflected by the high quantum yield, but the *cis/trans* ratio remained the same as that obtained with an ordinary triplet sensitizer, namely, 3:7.[43] The mechanism is thoroughly discussed in the literature.[43]

Table 9. Photoisomerization of 54 to 55 in the Presence of 9,10-Dicyanoanthracene (DCA)[43]

substrate	solvent	atmosphere	quantum yield[a] (Φ)
54a	acetonitrile	aerated	0.009
54b	acetonitrile	aerated	0.01
54d	acetonitrile	aerated	0.67
54d	acetonitrile	degassed	0.17
54d	acetonitrile	argon	0.23
54d	dichloromethane	aerated	0.25
54d	benzene	aerated	0.017

[a] Values at >400 nm irradiation with [DCA] = 5×10^{-4} mol·dm^{-3}, [**54**] = 1×10^{-2} mol·dm^{-3}.

Table 10. Effects of Sensitizers and Additives on the Photoisomerization of 54d to 55d in Aerated Acetonitrile Solution[43]

sensitizer	additive (concn, M)	quantum yield[a] (Φ)
9,10-dicyanoanthracene (DCA)		0.67
DCA	$LiClO_4$ (5×10^{-3})	2.57
DCA	$Mg(ClO_4)_2$ (2.5×10^{-3})	4.65
DCA	$Mg(ClO_4)_2$ (5×10^{-3})	13.7
DCA	biphenyl (1.5×10^{-3})	1.32
DCA	biphenyl (1×10^{-2})	1.87
DCA	phenanthrene (1×10^{-2})	3.33
chloranil (CHL)		0.80
CHL	$Mg(ClO_4)_2$ (2.5×10^{-3})	2.14

[a] Values at >400 nm irradiation with [DCA] = 5×10^{-4} mol·dm^{-3}, [CHL] = 5×10^{-4} mol·dm^{-3}, [**54d**] = 1×10^{-2} mol·dm^{-3}.

4.2. With Permanent Cleavage of the Cyclopropane Ring

4.2.1. By [3 + 2] Photocycloadditions

A triplet-sensitized [3 + 2] cycloaddition takes place when a mixture of acrylonitrile or methacrylonitrile, one of the 1-(2′,2′-diarylethenylidene)cyclopropane derivatives **56**, and Michler's ketone (MK)

Scheme 25

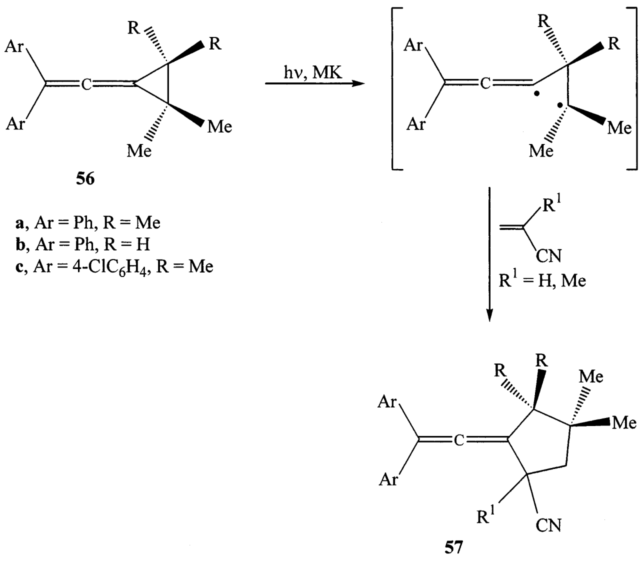


Table 11. [3 + 2] Photocycloaddition of 56 with Acrylonitrile Derivatives ($R^2CH{=}CR^1CN$) under Michler's Ketone Sensitization[42b]

cyclopropane	acrylonitrile	isolated yield of **57** (%)	recovered **56** (%)
56a	$R^1 = R^2 = H$	85	>5
56a	$R^1 = H, R^2 = Me$	0	>95
56a	$R^1 = Me, R^2 = H$	44	56
56b	$R^1 = R^2 = H$	71	>5
56b	$R^1 = Me, R^2 = H$	88	>5
56c	$R^1 = Me, R^2 = H$	32	62

is dissolved in benzene and irradiated under argon.[42,44] In each case the almost exclusive product is the corresponding 1-(2′,2′-diarylethenylidene)cyclopentane-2-carbonitrile (**57**) (Scheme 25), but the yield varies with the structure of both the nitrile and the allene (Table 11). It is noteworthy that 2,2,3,3-tetramethyl-1-(2′,2′-diphenylethenylidene)cyclopropane (**56a**) gives no cycloadduct when irradiated in the presence of crotononitrile.[42] The reaction is believed to involve a diradical intermediate.[42,45]

An interesting feature of the MK-sensitized cycloadditions of **56** with acrylonitrile and methacrylonitrile is the absence of products due to any reaction with the cyano group. This is obviously due to the presence of the C−C double bond in these nitriles, because when mixtures of 1-[2′,2′-bis(4-methoxyphenyl)ethenylidene]-2,2,3,3-tetramethylcyclopropane (**58a**) or 1-[2′,2′-bis(4-methoxyphenyl)ethenylidene]-2,2,3-trimethylcyclopropane (**58b**) and a saturated nitrile or benzonitrile are photolyzed in the presence of 9,10-dicyanoanthracene (DCA), a [3 + 2] cycloaddition across the cyano group takes place.[42b] The products, the corresponding 2-alkyl- or 2-phenyl-substituted 1-pyrrolines (**59**) (Scheme 26), were formed in low yields, but when the photolyses were repeated after the addition of $Mg(ClO_4)_2$, **59** was obtained in good to excellent yields (Table 12). The crucial step in the reaction is the electron transfer from **58** to DCA to give $\mathbf{58}^{\bullet+}$, which reacts with the cyano group to afford the products.[42b]

Scheme 26

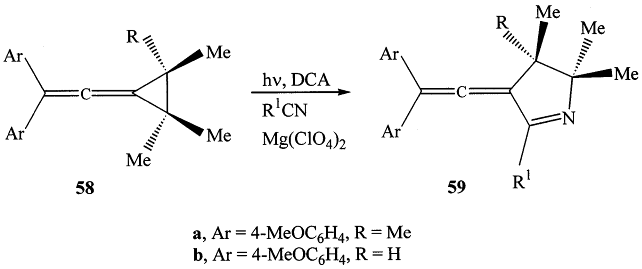
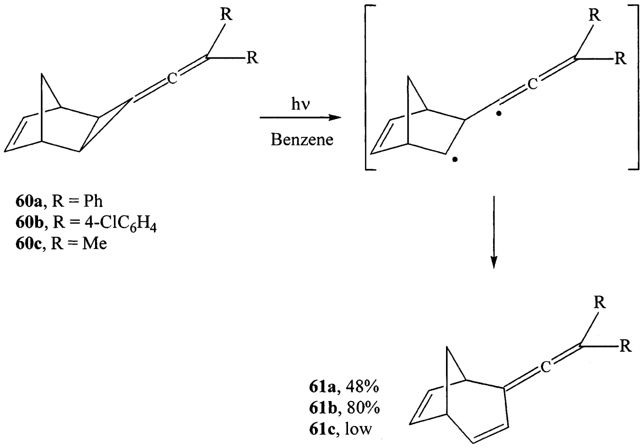


Table 12. [3 + 2] Photocycloaddition of 58 with Organic Carbonitriles under 9,10-Dicyanoanthracene Sensitization in the Presence of Magnesium Perchlorate[42b]

ethenylidenecyclopropane	organic carbonitrile	isolated yield of **59** (%)
58a	MeCN	86
58a	EtCN	88
58a	*n*-PrCN	68
58a	*n*-$C_5H_{11}CN$	67
58a	i-PrCN	69
58a	*t*-BuCN	64
58a	PhCN	90
58b	MeCN	89

Scheme 27

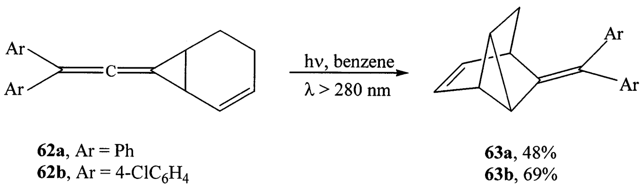


The photoinduced reactivity of **56a** toward some other alkenes under triplet-sensitized conditions (Michler's ketone) has also been explored. The studies revealed that products were obtained in moderate yield (32%) with ethyl acrylate and methyl methacrylate, whereas no cycloaddition took place with styrene and 2-cyclohexenone.[42]

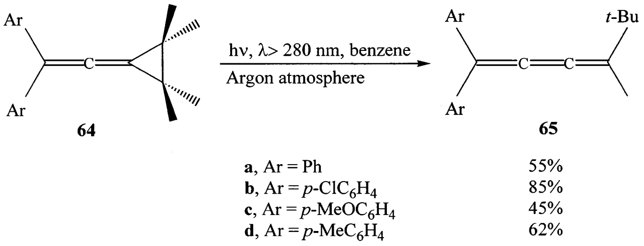
4.2.2. By Photorearrangements

Ethenylidenecyclopropanes have been proven to undergo photoinduced rearrangements if properly substituted and to afford allenes after cleavage of the cyclopropane ring. Irradiation of two *exo*-3-(2′,2′-diarylethenylidene)tricyclo[3.2.1.0^{2,4}]oct-6-enes (**60**) in benzene, either directly or by benzophenone or Michler's ketone sensitization, gave the corresponding 4-(2′,2′-diarylethenylidene)tricyclo[3.2.1]octa-2,6-dienes (**61**) in reactions, probably involving biradical intermediates (Scheme 27).[45] The dimethyl analogue to **60a**, tricyclooctene **60c**, did also react when irradiated with light of shorter wavelengths, but the corresponding product **61c** was obtained in low yield. The rearrangement, therefore, seems to lack generality, and this proved to be the case by the observation

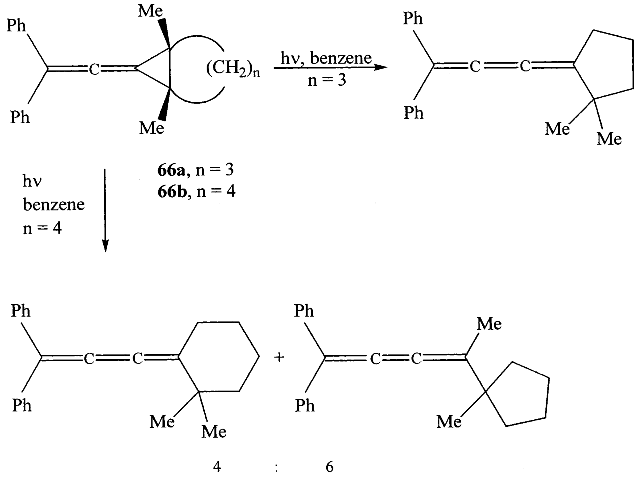
Scheme 28



Scheme 29



Scheme 30

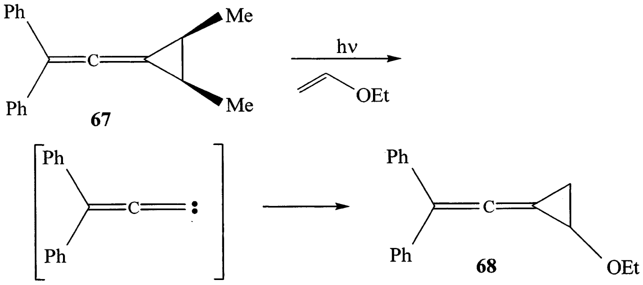


that when two 7-(2′,2′-diarylethenylidene)bicyclo[4.1.0]hept-2-enes (**62**) were irradiated just like **60**, no allenes, but completely different products, namely, the corresponding 8-(2′,2′-diarylmethenylidene)tricyclo[3.2.1.0^{4,6}]oct-2-enes (**63**), were obtained (Scheme 28).[45]

A different rearrangement occurred when some 1-(2′,2′-diarylethenylidene)cyclopropanes were dissolved in benzene and irradiated through Pyrex under argon atmosphere. When selected 1-(2′,2′-diarylethenylidene)-2,2,3,3-tetramethylcyclopropanes (**64**) were exposed to these conditions, the corresponding 1,1-diaryl-4,5,5-trimethyl-1,2,3-hexatriene (**65**) was obtained as the only product (Scheme 29).[46] The same photorearrangement took place when the bicyclic ethenylidenecyclopropanes **66a** and **66b** were irradiated under the same conditions (Scheme 30).[46] Mechanistic studies showed that the rearrangement was neither sensitized by triplet sensitizers nor quenched by isoprene or molecular oxygen, observations which are indicative of a transformation involving one or several singlet biradical intermediates.[46]

A similar allene, *cis*-2,3-dimethyl-1-(2′,2′-diphenylethenylidene)cyclopropane (**67**), behaved differently upon irradiation through Pyrex in various other solvents.[42b] In methanol, no product was isolated, but when the reaction was performed in ethyl vinyl ether, 2-ethoxy-1-(2′,2′-diphenylethenylidene)cyclopropane (**68**) was obtained in 25% yield. Most likely diphenylethenylidenecarbene is involved as an intermediate, but the species is unstable and is trapped by the ether (Scheme 31). An analogous reaction occurs when the reaction is run in cyclohexene, but the yield of the corresponding ethenylidenecyclopropane is low.[42b]

Scheme 31



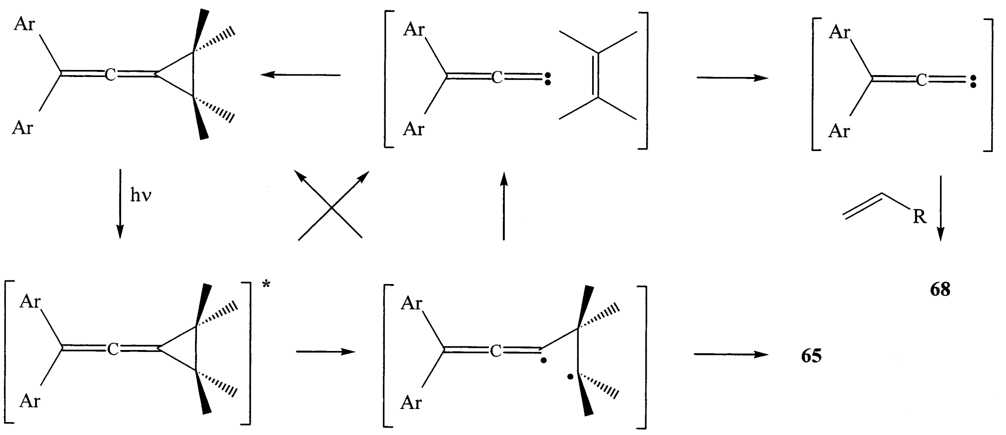
On the basis of the results of the photolyses of ethenylidenecyclopropanes **64** and **67** the mechanism outlined in Scheme 32 has been proposed for the formation of butatriene derivatives and the generation of ethenylidene carbenes.[46] Butatriene formation is envisaged to involve a biradical, which, however, can also collapse to the corresponding diarylethenylidenecarbene required to give ethenylidenecyclopropane derivatives.

4.2.3. By Thermal Rearrangements

The rearrangement of vinylcyclopropanes to cyclopentenes is a useful method for the synthesis of substituted five-membered ring systems, although the reaction usually requires heating above 180 °C to work.[47] However, when the vinylcyclopropane has a 2′,2′-diphenylethenylidene substituent attached to the ring as well, as in **69**, the reaction proceeds at a much lower temperature, as low as 100 °C, and furnishes the corresponding 4-(2′,2′-diphenylethenylidene)cyclopent-1-ene (**70**) (Scheme 33) in essentially quantitative yield in the best cases (Table 13).[48] Despite the good yields, the reaction rate varies considerably; this is clearly reflected in the half-life and thermodynamic values compiled in Table 14. The data are compatible with a radical mechanism involving a biradical formed in a facile fashion by cleavage of the cyclopropane ring.[47] This explains why the *trans* isomer of 1-(2′,2′-diphenylethenylidene)-3-methyl-2-(1*E*-propenyl)cyclopropane (**71**) gives a *cis*/*trans* mixture of 4-(2′,2′-diphenylethenylidene)-3,5-dimethylcyclopent-1-ene (**72**) upon thermolysis (Scheme 34).

Two compounds deviate from the general reactivity pattern summarized above. One is 1-(2′-methylpropenylidene)-2-methyl-2-ethenylcyclopropane, which is unreactive even above 120 °C. Because **69c** reacts under these conditions (Scheme 33; Table 13), it is clear that cleavage of the cyclopropane ring in **69** is facilitated by the phenyl groups. Furthermore, thermolysis of 2,2-dimethyl-1-(2′,2′-diphenylethenylidene)-3-(2′-methylprop-1′-enyl)cyclopropane (**73**) at 100 °C did not give the expected cyclopentene **74**; instead, the 1,2-dimethylene-3-ethenylcyclopropane derivative

Scheme 32



Scheme 33

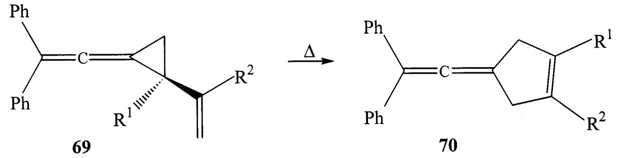
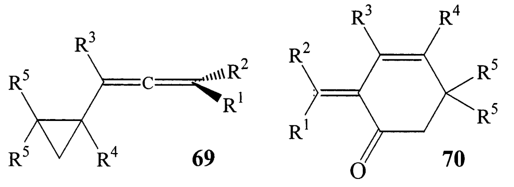


Table 13. Formation of 70 by Thermolysis[a] of 69[48]

substrate	R1, R2	isolated yield of **70** (%)
69a	H, H	95
69b	H, Me	82
69c	Me, H	90
69d	Me, Me	88
69e	$-(CH_2)_4-$	92

[a] All of the reactions except one were run at 373 K; the exception is the thermolysis of **59d**, which was run at 323 K. [b] 7-(2′,2′-Diphenylethenylidene)bicyclo[4.1.0]hept-2-ene reacts similarly to **69** and gives 7-(2′,2′-diphenylethenylidene)bicyclo-[2.2.1]hept-2-ene in 69% yield.

Table 14. Activation Parameters for the Thermal Conversion of 69 to 70[48]



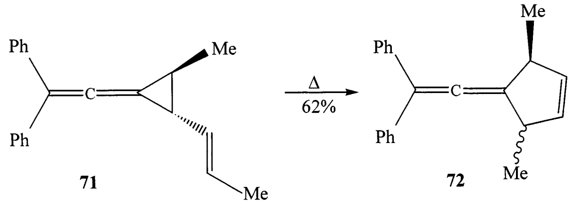
substrate	$\tau_{1/2}$ (s) at 363 K	$\Delta H^{\#}$ (kJ mol^{-1})	$\Delta S^{\#}$ (J mol^{-1} K^{-1})
69a	301	116	22
69b	1227	122	27
69c	37	95	−19
69d	138	105	−2
69e	49	98	−13
69f	563	98	−33
69g	2123	132	30

75 was obtained in 67% yield (Scheme 35), conceivably because the ring bond opposite C-1 was cleaved instead of that next to it.[48]

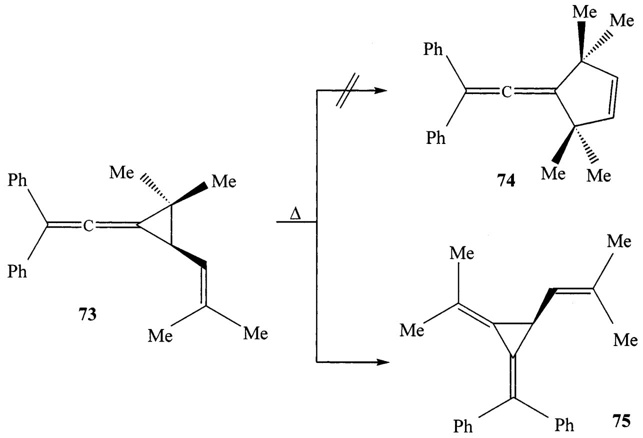
5. Reactions with Cyclopropylallenes

The proximity of the cyclopropane ring and allene moiety in the cyclopropylallene group allows interaction between two chemical entities with rather different chemical properties. It is therefore reasonable to believe that this interaction mutually modifies the chemical reactivity of the groups and facilitates chemical reactions that are otherwise difficult to achieve. Recent publications indicate that such interactions have chemical consequences which are about to be uncovered; some of this chemistry is therefore presented here.

Scheme 34



Scheme 35

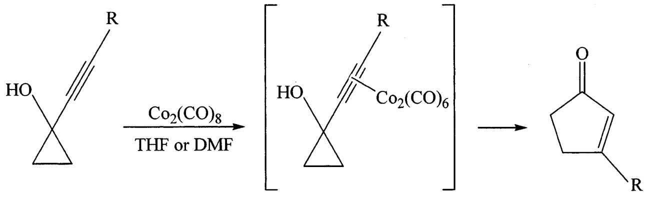


5.1. Metal-Catalyzed Ring Expansion

5.1.1. With Cobalt Carbonyl

Around 1990 Iwasawa and co-workers discovered that when 1-(1-alkynyl)cyclopropanols were treated with dicobaltoctacarbonyl [$Co_2(CO)_8$], complexation followed by ring opening and subsequent condensation occurred to give 2-cyclopentenones in good yields (Scheme 36).[49] This observation, combined with $Co_2(CO)_8$-mediated transformations of allenes reported previously,[50] led to the development of a new 1,4-hydroquinone synthesis based on treatment of 1-(1-allenyl)cyclopropanols with $Co_2(CO)_8$. Two of the

Scheme 36



Scheme 37

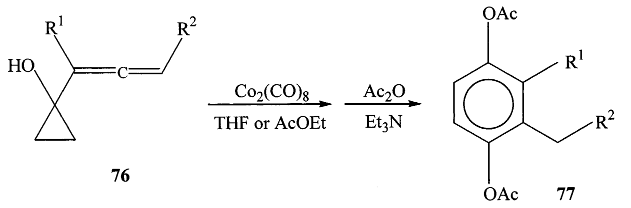


Table 15. Formation of 77 by Treating 76 with $Co_2(CO)_8$ Followed by Acetic Anhydride and Triethylamine in THF or AcOEt[51]

substrate	R^1	R^2	reaction conditions	yield of **77** (%)
76a	Ph	H	rt, 4 h	78
76b	*n*-C_6H_{13}	H	rt, 1 h	60
76c	Me_3Si	H	rt, 1 h	90[a]
76d	*t*-$BuMe_2Si$	H	rt, 2 days	87
76e	H	Ph	0 °C, 2 days	56
76f	H	*n*-C_6H_{13}	rt, 2 h	51

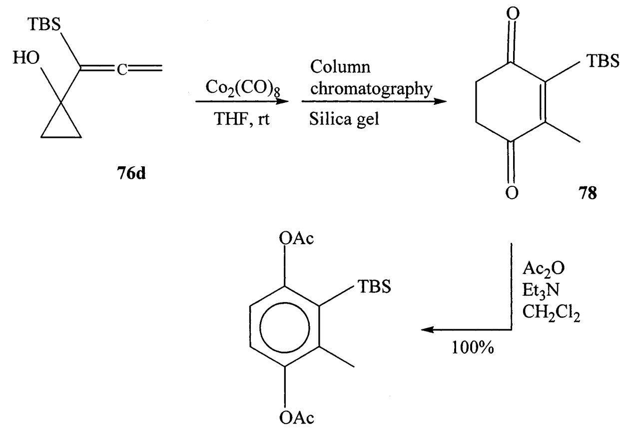
[a] A mixture of **77c** (47%) and the corresponding desilylated compound, 2-methyl-1,4-hydroquinone diacetate (43%).

cyclopropylallenes used were obtained by ring opening of the corresponding *tert*-butyldimethylsilyl-protected *gem*-dibromocyclopropanes (see section 2.2).[51]

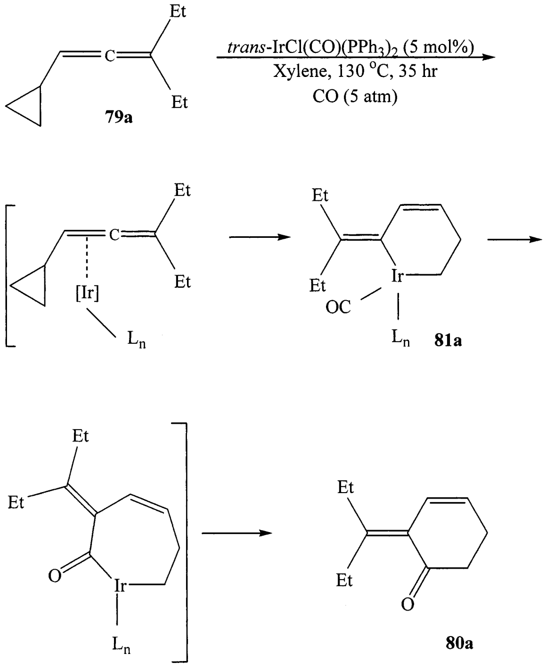
Exploratory experiments using 1-(1-phenylallenyl)-cyclopropanol revealed that the reaction was sensitive to several parameters including the reaction atmosphere, the solvent, the amount of catalyst and its concentration, and the workup procedure.[51] Analysis of the results showed that the outcome was best when the reaction was run in THF or ethyl acetate with 1.1 equiv of $Co_2(CO)_8$ at low concentration and when byproduct formation was suppressed by adding acetic anhydride to trap the intermediate hydroquinone. Under these conditions a selection of cyclopropanols **76** with a substituent at the 1- or 3-position of the propadienyl moiety were reacted with 1.1 molar amounts of $Co_2(CO)_8$ in either THF or AcOEt to give 2-substituted or 2,3-disubstituted 1,4-hydroquinone diacetates (**77**) in good to excellent yield (Scheme 37) (Table 15).

When reactions with some of the cyclopropanols were followed by TLC analysis, it turned out that an intermediate was formed, which gradually disappeared as the hydroquinone was formed. Isolation of this transient species was successful when 1-(1-*tert*-butyldimethylsilylallenyl)cyclopropanol (**76d**) was used. Careful workup by silica gel column chromatography gave 2-*tert*-butyldimethylsilyl-3-methylcyclohex-2-en-1,4-dione (**78**), which was converted quantitatively to the corresponding hydroquinone diacetate by treatment with acetic anhydride and triethylamine (Scheme 38). On this basis a plausible mechanism for the reaction has been proposed.[51]

Scheme 38



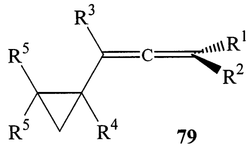
Scheme 39



5.1.2. With an Iridium Complex

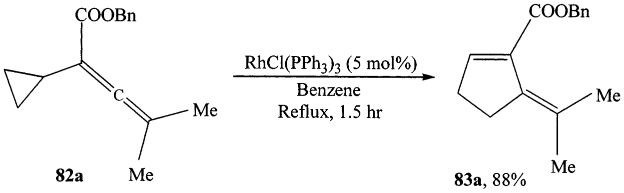
Several studies have shown that vinylallenes readily bind to metals and form complexes,[52] which may engage in both [4 + 1][53] and [4 + 2] cycloaddition[54] reactions. A natural extension of these investigations would be to study the interaction of the same metal complexes with cyclopropylallene derivatives. The first studies were carried out with rhodium(I) complexes, both neutral, for example, $RhCl(CO)(PPh_3)_2$, and cationic ones (which are potent catalysts for the [4 + 1] cycloaddition of vinylallene with carbon monoxide),[52d] but no carbonylation took place, only isomerization to methylenecyclopentene derivatives.[55] However, application of similar complexes involving other transition metals revealed that $IrCl(CO)(PPh_3)_2$ is a powerful catalyst, which facilitates a [5 + 1] cycloaddition reaction with CO.[56] When the substituted cyclopropylallene **79a** was exposed to CO under the conditions specified in Scheme 39, the α,*β*-unsaturated ketone **80a** was obtained in 81% yield. The formation of this ketone conceivably involves several intermediate iridium complexes due to the

Table 16. Iridium-Catalyzed [5 + 1] Cycloaddition of 79 with Carbon Monoxide to Give 80[56]



substrate	R^1	R^2	R^3	R^4	R^5	yield of **80** (%)
79a	Et	Et	H	H	H	81
79b	Me	Me	H	EtO	H	74
79c	Me	Ph	H	H	H	83
79d	Me	Me	Ph	H	H	81
79e	Me	Me	H	H	Ph	63
79f	H	Ph	H	H	H	28

Scheme 40



following series of events.[56] Initial coordination of the allenyl group brings the metal close to the cyclopropane ring, which interacts with and is opened by the metal to form the six-membered metallacycle **81a**. Subsequent insertion of CO into the Ir$-$C$_{sp^2}$ bond followed by reductive elimination gives **80a**, which formally is a [5 + 1] cycloaddition product.

Several other substituted allenylcyclopropanes were reacted with CO under iridium catalysis under the same conditions and afforded the corresponding 2-methylenecyclohex-3-en-1-ones in variable yields (Table 16). The product formation was particularly sensitive to the structural features at the terminus of the allene group. Thus, substrates with a disubstituted allene terminus gave **80** in good yield and compounds with a monosubstituted terminus in low yield, whereas allenylcyclopropanes without substituents at the terminus gave no **80** at all. The results can be understood on the basis of site preference for complexation of the allene moiety in the coordination process.[56]

5.1.3. With a Rhodium Complex

If the structure similarities between vinylcyclopropanes and the corresponding allenylcyclopropanes are reflected in their reactivity, it is reasonable to believe that allenylcyclopropanes should undergo a transition metal-mediated reaction analogous to the vinylcyclopropane$-$cyclopentene rearrangement. The idea was realized in 1998 when Saigo and co-workers managed to convert allenylcyclopropane **82a** to the corresponding methylenecyclopentene **83a** in an RhCl(PPh$_3$)$_3$-catalyzed process in excellent yield (Scheme 40).[57] The same group also tried to achieve the allenylcyclopropane$-$cyclopentene rearrangement with several other catalysts,[57] based on work by Wender et al., who reported that cationic rhodium complexes catalyze the [5 + 2] cycloaddition of vinylcyclopropanes with alkynes more quickly than a neutral rhodium complex.[58] It appeared that the ionic alternatives were slightly better than RhCl(PPh$_3$)$_3$, but the reaction time required to obtain good yields had to be extended in several cases.

Scheme 41

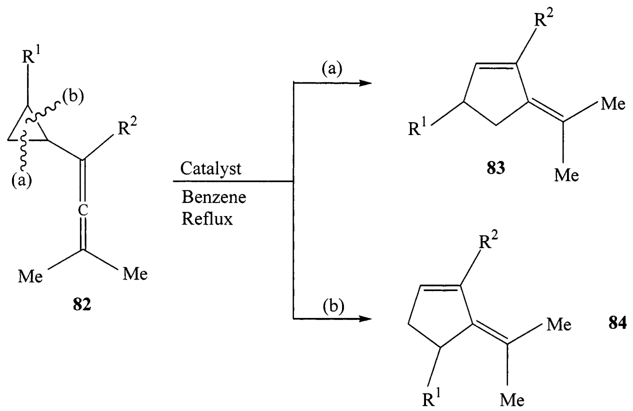


Table 17. Rhodium(I)-Catalyzed Rearrangement in Refluxing Benzene of 82 to Mixtures of 83 with 84[57]

substrate	R^1	R^2	catalyst[a]	time (h)	**83**:**84** ratio	combined yield of **83** and **84** (%)
82a	H	COOBu	A	1.5		88
82a	H	COOBu	B	3		88
82b	Pr	COOBu	A	1	88:12	89
82b	Pr	COOBu	C	3	>99:1	98
82b	Pr	COOBu	B	10	>99:1	89
82c	Ph	COOMe	A	3	69:31	99
82c	Ph	COOMe	C	0.8	92:8	98
82c	Ph	COOMe	B	14	5:95	95
82d	Ph	H	A	12	56:44	73
82d	Ph	H	D	12	15:85	79
82d	Ph	H	B	12	3:97	78

[a] The following catalysts were used: A, RhCl(PPh$_3$)$_3$; B, [Rh(cod)$_2$]$^+$BF$_4^-$; C, [Rh(PPh$_3$)$_3$]$^+$BF$_4^-$; D, [Rh(cod)(PPh$_3$)$_2$]$^+$BF$_4^-$; cod, 1,5-cyclooctadiene.

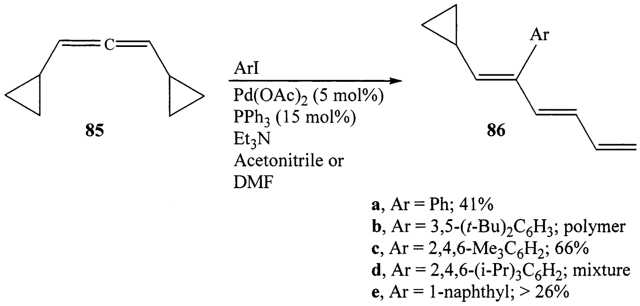
When **82** are 2-substituted 1-allenylcyclopropanes, the rearrangement can lead to two products because two different ring bonds can be broken. Cleavage of bond a will afford cyclopentene **83**, whereas rupture of bond b will give regioisomer **84** (Scheme 41). Generally, both cleavages are observed if both options are available, but the **83**:**84** ratio proved to depend on the catalyst as well as the nature of the substituent(s) attached to the ring. Thus, alkyl substitution at C-2 facilitates mainly a-bond rupture and formation of **83**, irrespective of the catalyst. 2-Phenyl-substituted substrates, on the other hand, were much more sensitive to the catalyst; thus, when **82c** was reacted, complete reversal of the regiochemistry was observed when the catalyst was changed from [Rh(PPh$_3$)$_3$]$^+$BF$_4^-$ to [Rh(cod)$_2$]$^+$BF$_4^-$ (Table 17). A similar, but less dramatic, change was observed when **72d** was reacted under comparable conditions (Table 17).[57]

The mechanism for this special version of the vinylcyclopropane$-$cyclopentene rearrangement has yet to be elucidated, but a mechanistic proposal has been put forward by Saigo and co-workers.[57]

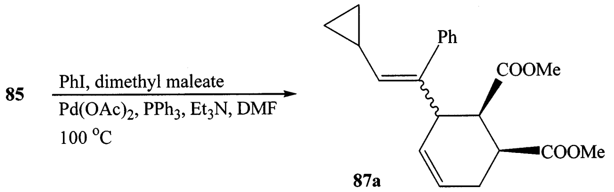
5.2. Ring Opening by Heck Reactions

Palladium-catalyzed addition of aryl and vinyl carbanions to olefins is a most useful catalytic reac-

Scheme 42



Scheme 43



tion in organic synthesis.[59] The reaction can be performed under a variety of conditions and with various reagents, which have given rise to a number of named Pd-based reactions including the Heck reaction,[59a,60] the Suzuki coupling,[61] the Stille coupling,[62] and the Sonogashira coupling.[63]

Pd catalysis has also been used to facilitate reactions with allenes, and it appears that the method is suitable to apply for introduction of carbon and heteroatom nucleophiles in specific positions in complex molecules.[64] Recently, de Meijere and co-workers extended the scope of the reaction by performing Heck reactions with 1,3-dicyclopropylallene (**85**) and aryl iodides, which gave 2-aryl-1-cyclopropylhexa-1,3,5-triene (**86**) as the principal volatile product (Scheme 42).[17c] Triene **86** appeared to be extremely prone to polymerization, but this undesired reaction could be suppressed by avoiding acidic conditions and prevent radical reactions from occurring by the addition of a small amount of hydroquinone.[17c]

Trienes **86** contain two diene systems, which both in principle can undergo Diels–Alder reactions with dienophiles. However, it appeared that the reaction with a variety of dienophiles was regioselective and furnished the cycloadduct resulting from attack of the monosubstituted diene. The best results were obtained when the trienes were prepared from **85**, as described above, in the presence of the dienophile (a so-called Domino–Heck–Diels–Alder reaction). An excellent example is cyclohexene **87a**, which was obtained in 86% yield from **85** and iodobenzene in such a synthesis (Scheme 43), but in general the cycloadducts were obtained in significantly lower yields (Table 18).[17c]

Table 18. Conversion of 85 to Cycloadducts 87 by a Domino-Heck-Diels–Alder Reaction Involving ArI and Selected Dienophiles[17c]

Ar	dienophile	yield of **87** (%)	diastereomeric ratio
Ph	dimethyl maleate	86	4:1
Ph	dimethyl fumarate	44	3.3:1
Ph	*N*-phenylmaleimide	35	
Ph	2-chloroacrylonitrile	58	1:4.3[a]
Ph	*p*-benzoquinone	13[b]	
Ph	diisopropyl azodicarboxylate	6	
Ph	*N*-phenyl-1,2,4-triazolin-3,5-dione	0	
1-naphthyl	dimethyl maleate	26	2.1:1
2-pyridyl	dimethyl maleate	35	4.9:1
3,5-(i-Pr)$_2$C$_6$H$_3$	dimethyl maleate	49	2.5:1
2,4,6-Me$_3$C$_6$H$_2$	dimethyl maleate	59	2.1:1
2,4,6-(i-Pr)$_3$C$_6$H$_2$	dimethyl maleate	0	

[a] The ratio between the ortho cycloadduct and the meta cycloadduct. [b] Oxidized to the corresponding naphthoquinone by excess benzoquinone.

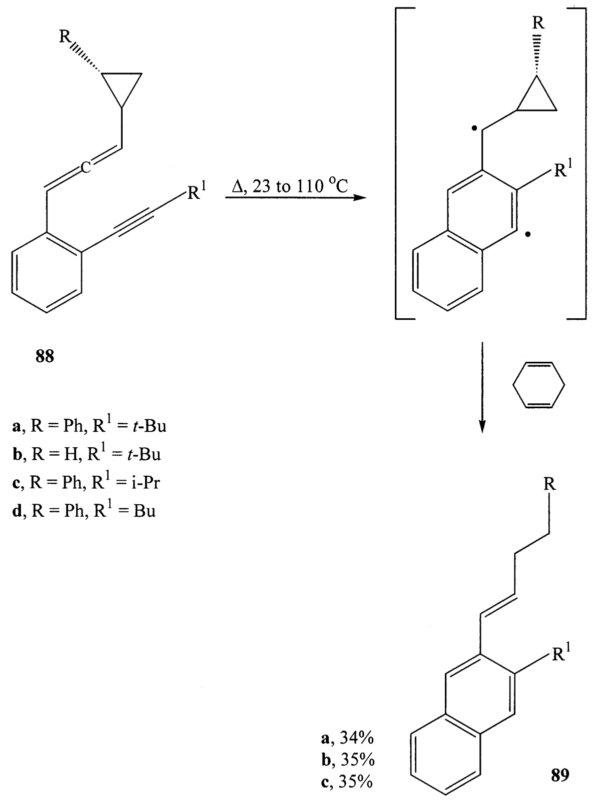
5.3. Myers–Saito Cyclization

The Myers–Saito cyclization is exhibited by compounds containing a (*Z*)-1,2,4-heptatrien-6-yne moiety, an enyne–allene group that is able to cyclize and afford α,3-didehydrotoluenes under mild thermal conditions.[65] Simple enyne–allenes cyclize at room temperature and even below, but the reaction rate is sensitive to the substituents on both the alkyne and allene groups. Dopico and Finn[66] have studied a large number of 1-ethynyl-2-allenylbenzene derivatives with substituents attached to the end of both the allenyl and ethynyl groups. Among the compounds investigated were four derivatives with a cyclopropyl group or a 2-phenylcyclopropyl group on the allenyl substituent (**88**), which were thermolyzed under a variety of conditions. The results clearly show that the course of the reaction depends on the reaction conditions. When **88a**–**c** were heated in the presence of 1,4-cyclohexadiene, naphthalene derivatives **89a**–**c** were obtained in 35% yield via, as expected,[65] a diradical intermediate, which undergoes ring opening like cyclopropylmethyl radicals do (Scheme 44).[67] In addition, **88a** and **88b**, both with a *tert*-butyl group on the alkyne, gave small amounts of allene dimers, but the amount of these byproducts could be minimized by running the reaction in diluted solutions.

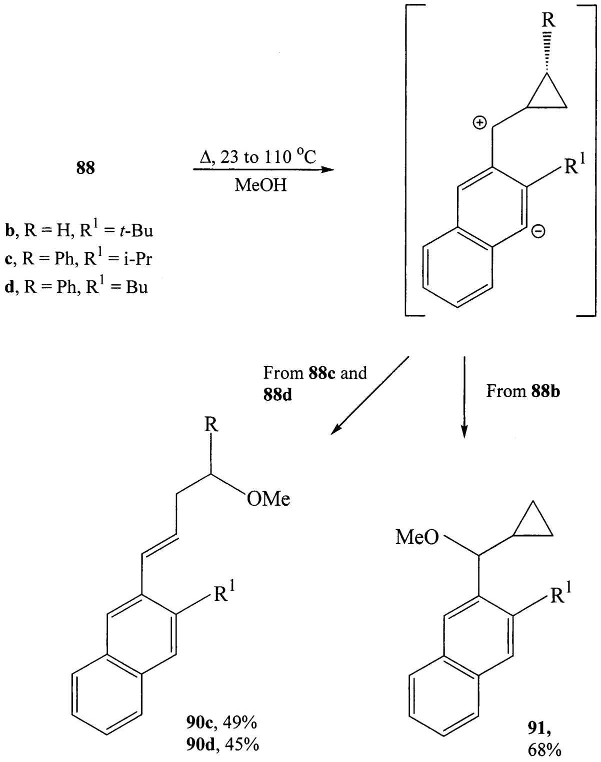
Allene enynes **88** were also heated in methanol, and under these conditions they appeared to react very differently. Allene **88a** produced an intractable product mixture, which was not worked up, whereas **88c** and **88d** gave methyl ether **90c** and **90d**, respectively, as the main product (Scheme 45). The formation of **90** conceivably involved a benzylic cation formed by ring opening of a zwitterionic intermediate, the transient existence of which is supported by the isolation of methyl ether **91**, in which the cyclopropyl ring remains intact, when **88b** is solvolyzed (Scheme 45).[66]

Dopico and Finn also performed thorough kinetic studies, which clearly reveal that allene enynes **88** react much more slowly than analogues with a phenyl or aryl group attached to the allenyl group.[66] It can therefore be concluded that the Myers–Saito cyclization does not benefit from a cyclopropyl or phenylcyclopropyl group on the allene moiety. The same is true when R^1 in **88** is an aryl group; such compounds afford benzofulvenes instead of naphthalenes whether a cyclopropyl group is attached to the allene moiety or not.[68]

Scheme 44



Scheme 45



6. References

(1) The first allene was in fact synthesized in 1887 by Burton and Pechmann (Burton, B. S.; Pechmann, H. V. *Ber. Dtsch. Chem. Ges.* **1887**, *20*, 145), but the structure of the compound was not elucidated until 1954 by Jones et al. (Jones, E. R. H.; Mansfield, G. H.; Whiting, M. C. *J. Chem. Soc.* **1954**, 3208).

(2) Gustavson, G.; Demjanov, N. *J. Prakt. Chem.* **1888**, *38*, 201.

(3) Relevant books: (a) Murray, M. In *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; Thieme Verlag: Stuttgart, Germany, 1977; Vol. 5/2a, p 1063. (b) *The Chemistry of Allenes*; Landor, S. R., Ed.; Academic Press: London, U.K., 1982. (c) Schuster, H. F.; Coppola, G. M. *Allenes in Organic Syntheses*; Wiley: New York, 1984. (d) Taber, A. M.; Mushina, E. A.; Krentsel, B. A. *Allenic Hydrocarbons: Synthesis, Properties and Applications*; Nauka: Moscow, Russia, 1987 (in Russian). (e) Saalfrank, R. W.; Lurz, C.-J. In *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; Thieme Verlag: Stuttgart, Germany, 1993; Vol. E 15/3, p 2959. (f) *The Chemistry of the Cyclopropyl Group*; Rappoport, Z., Ed.; Wiley: Chichester, U.K., 1987; Vol. 2. (g) Hopf, H. *Classics in Hydrocarbon Chemistry*; Wiley: Chichester, U.K., 2000.

(4) Review articles: (a) Marshall, J. A. *Chem. Rev.* **1996**, *96*, 31. (b) Wang, K. K. *Chem. Rev.* **1996**, *96*, 207. (c) Negishi, E.; Copéret, C.; Ma, S.; Lou, S.-Y.; Liu, F. *Chem. Rev.* **1996**, *96*, 365. (d) Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A. *Chem. Rev.* **2000**, *100*, 3067. (e) Smith, N. D.; Mancuso, J.; Lautens, M. *Chem. Rev.* **2000**, *100*, 3257. (f) Lu, X.; Zhang, C.; Xu, Z. *Acc. Chem. Res.* **2001**, *34*, 535.

(5) Doering, W. v. E.; LaFlamme, P. M. *Tetrahedron* **1958**, *2*, 75.

(6) (a) Moore, W. R.; Ward, H. R. *J. Org. Chem.* **1960**, *25*, 2073. (b) Moore, W. R.; King, B. M. *J. Org. Chem.* **1971**, *36*, 1877.

(7) (a) Skattebøl, L. *Tetrahedron Lett.* **1961**, 167. (b) Skattebøl, L. *Acta Chem. Scand.* **1963**, *17*, 1683.

(8) (a) Wendisch, D. In *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; Thieme Verlag: Stuttgart, Germany, 1971; Vol. 4/3. (b) Kirmse, W. *Carbene Chemistry*, 2nd ed.; Academic Press: New York, 1971. (c) Jones, W. M.; Brinker, U. H. *Some Pericyclic Reactions*; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977. (d) *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; Regitz, M., Ed.; Thieme Verlag: Stuttgart, Germany, 1989; Vol. E 19b, Parts 1 and 2. (e) Boche, G.; Walborsky, H. M. *Cyclopropane Derived Reactive Intermediates*; Patai, S., Rappoport, Z., Eds.; Wiley: Chichester, U.K., 1990. (f) *Houben-Weyl, Methods of Organic Chemistry*, 4th ed.; de Meijere, A., Ed.; Thieme Verlag: Stuttgart, Germany, 1997; Vol. E 17b. (g) *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; de Meijere, A., Ed.; Thieme Verlag: Stuttgart, Germany, 1997; Vol. E 17c. (h) Bettinger, H. F.; v. R. Schleyer, P.; Schreiner, P. R.; Schaefer, III, H. F. *J. Org. Chem.* **1997**, *62*, 9267. (i) Bettinger, H. F.; Schreiner, P. R.; v. R. Schleyer, P.; Schaefer, III, H. F. *J. Phys. Chem.* **1996**, *100*, 16147.

(9) (a) Skattebøl, L. *Chem. Ind. (London)* **1962**, 2146. (b) Skattebøl, L. *Tetrahedron* **1967**, *23*, 1107. (c) Holm, K. H.; Skattebøl, L. *Tetrahedron Lett.* **1977**, 2347. (d) Holm, K. H.; Skattebøl, L. *Acta Chem. Scand. Ser. B* **1984**, *38*, 783. (e) Zimmermann, H. E.; Kreil, D. J. *J. Org. Chem.* **1982**, *47*, 2060. (f) Brinker, U. H.; Boxberger, M. *J. Chem. Res. (S)* **1983**, 100. (g) McLaughlin, M. L.; McKinney, J. A.; Paquette, L. A. *Tetrahedron Lett.* **1986**, *27*, 5595.

(10) (a) Moore, W. R.; Taylor, K. G.; Müller, P.; Hall, S. S.; Gaibel, Z. L. F. *Tetrahedron Lett.* **1970**, 2365. (b) Moore, W. R.; Hill, J. B. *Tetrahedron Lett.* **1970**, 4553. (c) Reinarz, R. B.; Fonken, G. J. *Tetrahedron Lett.* **1973**, 4595. (d) Brown, D. W.; Hendrick, M. E.; Jones, Jr., M. *Tetrahedron Lett.* **1973**, 3951. (e) Baird, M. S. *J. Chem. Soc., Chem. Commun.* **1979**, 776.

(11) (a) Sydnes, L. K.; Skattebøl, L. *Acta Chem. Scand. Ser. B* **1978**, *32*, 547. (b) Jendralla, H.; Pflaumbaum, W. *Chem. Ber.* **1982**, *115*, 210. (c) Sydnes, L. K.; Skare, S. *Can. J. Chem.* **1984**, *62*, 2073. (d) Skattebøl, L.; Nilsen, N. O.; Myhren, F. *Acta Chem. Scand. Ser. B* **1986**, *40*, 782. (e) Skattebøl, L.; Stenström, Y.; Stjerna, M.-B. *Acta Chem. Scand. Ser. B* **1988**, *42*, 475. (f) Miebach, T.; Wüster, H.; Brinker, U. H. *J. Org. Chem.* **1993**, *58*, 6520. (g) Miebach, T.; Brinker, U. H. *J. Org. Chem.* **1993**, *58*, 6524. (h) Brinker, U. H.; Miebach, T. *J. Org. Chem.* **1999**, *64*, 8000.

(12) Baird, M. S.; Huber, F. A. M.; Tverezovsky, V. V.; Bolesov, I. G. *Tetrahedron* **2000**, *56*, 4799.

(13) (a) Baird, M. S. *Tetrahedron Lett.* **1984**, *25*, 4829. (b) Baird, M. S.; Buxton, S. R.; Hussain, H. H. *J. Chem. Res. (S)* **1986**, 310. (c) Al Dulayymi, J. R.; Baird, M. S.; Fitton, H. L. *Tetrahedron Lett.* **1992**, *33*, 4803. (d) Al Dulayymi, J. R.; Baird, M. S.; Rajaram, L.; Fitton, H. L. *J. Chem. Soc., Perkin Trans. 1* **1994**, 1633.

(14) Al Dulayymi, J. R.; Baird, M. S. *Tetrahedron Lett.* **1995**, *36*, 3393.

(15) (a) Satoh, T.; Takano, K. *Tetrahedron* **1996**, *52*, 2349. (b) Satoh, T.; Takano, K.; Ota, H.; Someya, H.; Matsuda, K.; Koyama, M. *Tetrahedron* **1998**, *54*, 5557. (c) Satoh, T. *J. Synth. Org. Chem. Jpn.* **1996**, *54*, 481.

(16) Satoh, T.; Kurihara, T.; Fujita, K. *Tetrahedron* **2001**, *57*, 5369.

(17) (a) Creary, X.; Jiang, Z.; Butchko, M.; McLean, K. *Tetrahedron Lett.* **1996**, *37*, 579. (b) Owada, Y.; Matsuo, T.; Iwasawa, N. *Tetrahedron Lett.* **1997**, *38*, 11069. (c) de Meijere, A.; Knoke, M. Personal communication.

(18) (a) Johnson, R. P. *Chem. Rev.* **1989**, *89*, 1111. (b) Jelinek-Fink, H.; Christl, M.; Peters, E.-M.; Peters, K.; von Schnering, H. G. *Chem. Ber.* **1991**, *124*, 2569.

(19) (a) Özen, R.; Balci, M. *Tetrahedron* **2002**, *58*, 3079. (b) Algi, F.; Özen, R.; Balci, M. *Tetrahedron* **2002**, *43*, 3129.

(20) Christl, M.; Groetsch, S.; Günther, K. *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 3261.

(21) (a) Moore, W. R.; Ward, H. R.; Merritt, R. F. *J. Am. Chem. Soc.* **1961**, *83*, 2019. (b) Marquis, E. M.; Gardner, P. D. *J. Chem. Soc., Chem. Commun.* **1966**, 726. (c) Backes, J.; Brinker, U. H. In *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; Regitz, M., Ed.; Thieme Verlag: Stuttgart, Germany, 1989; Vol. E 19b, Part 1, p 430.

(22) Moore, W. R.; Moser, W. R. *J. Org. Chem.* **1970**, *35*, 908.

(23) Santelli-Rouvier, C.; Toupet, L.; Santelli, M. *J. Org. Chem.* **1997**, *62*, 9039.

(24) (a) Banwell, M. G.; Hockless, D. C. R.; Walter, J. M. *J. Chem. Soc., Chem. Commun.* **1996**, 1469. (b) Banwell, M. G.; Hockless, D. C. R.; Longmore, R. W.; Walter, J. M. *Aust. J. Chem.* **1997**, *50*, 457.

(25) (a) Loosli, T.; Borer, M.; Kulakowska, I.; Minger, A.; Neuenschwander, M. *Helv. Chim. Acta* **1995**, *78*, 1144. (b) Borer, M.; Loosli, T.; Minger, A.; Neuenschwander, M. *Helv. Chim. Acta* **1995**, *78*, 1311. (c) Läng, C.; Mühlebach, M.; Neuenschwander, M. *Helv. Chim. Acta* **1997**, *80*, 2124. (d) Huwyler, R.; Li, X.; Bönzli, P.; Neuenschwander, M. *Helv. Chim. Acta* **1999**, *82*, 1242. (e) Borer, M.; Neuenschwander, M. *Helv. Chim. Acta* **1997**, *80*, 2486. (f) Huwyler, R.; Al-Dulayymi, A.; Neuenschwander, M. *Helv. Chim. Acta* **1999**, *81*, 2336. (g) Li, X.; Neuenschwander, M. *Helv. Chim. Acta* **2000**, *83*, 562.

(26) Kirms, M. A.; Salcido, S. L.; Kirms, L. M. *Tetrahedron Lett.* **1995**, *36*, 7979.

(27) (a) Seyferth, D.; Prokai, B. *J. Org. Chem.* **1966**, *31*, 1702. (b) Seyferth, D.; Lambert, R. L. *J. Organomet. Chem.* **1973**, *55*, C53. (c) Al Dulayymi, J. R.; Baird, M. S.; Bolesov, I. G.; Nizovtsev, A. V.; Tverezovsky, V. V. *J. Chem. Soc., Perkin Trans. 2* **2000**, 1603.

(28) (a) Inoue, R.; Shinokubo, H.; Oshima, K. *Tetrahedron Lett.* **1996**, *37*, 5377. (b) Inoue, A.; Kondo, J.; Shinokubo, H.; Oshima, K. *Chem. Eur. J.* **2002**, *8*, 1730.

(29) Baird, M. S.; Nizovtsev, A. V.; Bolesov, I. G. *Tetrahedron* **2002**, *58*, 1581.

(30) (a) Baird, M. S.; Nethercott, W. *Tetrahedron Lett.* **1983**, *24*, 605. (b) Stämpfli, U.; Neuenschwander, M. *Chimia* **1988**, *42*, 379. (c) Baird, M. S.; Fitton, H. L.; Clegg, W.; McCamley, A. *J. Chem. Soc., Perkin Trans. 1* **1993**, 321. (d) Al Dulayymi, J. R.; Baird, M. S.; Clegg, H. L. *Tetrahedron Lett.* **1992**, *33*, 4803. (e) Baird, M. S.; Hussain, H. H.; Nethercott, W. *J. Chem. Soc., Perkin Trans. 1* **1986**, 1845. (f) Billups, W. E.; Haley, M. M.; Lee, G.-A. *Chem. Rev.* **1989**, *89*, 1147. (g) Halton, B.; Banwell, M. G. Cyclopropenes. In *The Chemistry of the Cyclopropyl Group*; Rappoport, Z., Ed.; Wiley: New York, 1987; Chapter 1. (h) Billups, W. E.; Lee, G.-A.; Arney, B. E., Jr.; Whitmire, K. H. *J. Am. Chem. Soc.* **1991**, *113*, 7980. (i) Lee, G.-A.; Shiau, C.-S.; Chen, C.-S.; Chen, J. *J. Org. Chem.* **1995**, *60*, 3565.

(31) Kirms, M. A.; Primke, H.; Stohlmeier, M.; de Meijere, A. *Recl. Trav. Chim. Pays-Bas* **1986**, *105*, 462.

(32) (a) Padwa, A. *Acc. Chem. Res.* **1979**, 310. (b) Graf von der Schulenburg, W.; Hopf, H.; Walsh, R. *Chem. Eur. J.* **2000**, *6*, 1963.

(33) de Meijere, A.; Faber, D.; Heinecke, U.; Walsh, R.; Müller, T.; Apeloig, Y. *Eur. J. Org. Chem.* **2001**, 663.

(34) Skattebøl, L. *J. Org. Chem.* **1966**, *31*, 2789.

(35) (a) Bengtson, G.; Keyaniyan, S.; de Meijere, A. *Chem. Ber.* **1986**, *119*, 3607. (b) de Meijere, A.; Schulz, T.-J.; Kostikov, R. R.; Graupner, F.; Murr, T.; Bielfeldt, T. *Synthesis* **1991**, 547. (c) Militzer, H.-C.; Schömenauer, S.; Otte, C.; Puls, C.; Hain, J.; Bräse, S.; de Meijere, A. *Synthesis* **1993**, 998. (d) Bräse, S.; Schömenauer, S.; McGaffin, G.; Stolle, A.; de Meijere, A. *Chem. Eur. J.* **1996**, *2*, 545. (e) Flynn, B. L.; de Meijere, A. *J. Org. Chem.* **1999**, *64*, 400.

(36) Militzer, H.-C.; Schömenauer, S.; Otte, C.; Puls, C.; Hain, J.; Bräse, S.; de Meijere, A. *Synthesis* **1993**, 998.

(37) Emme, I.; Bruneau, C.; de Meijere, A.; Dixneuf, P. H. *Synlett* **2000**, 1315.

(38) Bruneau, C.; Kabouche, Z.; Neveux, M.; Seiller, B.; Dixneuf, P. H. *Inorg. Chim. Acta* **1994**, *222*, 155.

(39) Kitagawa, T.; Kamada, J.; Minegishi, S.; Takeuchi, K. *Org. Lett.* **2000**, *2*, 3011.

(40) Stang, P. In *Houben-Weyl, Methoden der Organischen Chemie*, 4th ed.; Regitz, M., Ed.; Thieme Verlag: Stuttgart, Germany, 1989; Vol. E 19b, Part 1, p 139.

(41) Isagawa, K.; Mizuno, K.; Sugita, H.; Otsuji, Y. *J. Chem. Soc., Perkin Trans. 1* **1991**, 2283.

(42) (a) Mizuno, K.; Sugita, H.; Hirai, T.; Maeda, H. *Chem. Lett.* **2000**, 1144. (b) Mizuno, K.; Ichinose, N.; Yoshimi, Y. *J. Photochem. Photobiol. C: Photochem. Rev.* **2000**, *1*, 167.

(43) Mizuno, K.; Nire, K.; Sugita, H.; Maeda, H. *Tetrahedron Lett.* **2001**, *42*, 2689.

(44) Mizuno, K.; Sugita, H.; Hirai, T.; Maeda, H.; Otsuji, Y.; Yasuda, M.; Hashiguchi, M.; Shima, K. *Tetrahedron Lett.* **2001**, *42*, 3363.

(45) Mizuno, K.; Sugita, H.; Isagawa, K.; Goto, M.; Otsuji, Y. *Tetrahedron Lett.* **1993**, *34*, 5737.

(46) Mizuno, K.; Maeda, H.; Sugita, H.; Nishioka, S.; Hirai, T.; Sugimoto, A. *Org. Lett.* **2001**, *3*, 581.

(47) See the following reviews: (a) Hudlicky, T.; Kutchan, T. M.; Naqvi, S. M. *Org. React.* **1985**, *33*, 247 and references therein. (b) Hudlicky, T.; Reed, J. W. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Paquette, L. A., Eds.; Pergamon: Oxford, U.K., 1991; Vol. 5, p 899. (c) Hopf, H. In *Houben-Weyl, Methods of Organic Chemistry*, 4th ed.; de Meijere, A., Ed.; Thieme Verlag: Stuttgart, Germany, 1997; Vol. E 17b, p 2526.

(48) Mizuno, K.; Sugita, H.; Kamada, T.; Otsuji, Y. *Chem. Lett.* **1994**, 449.

(49) (a) Iwasawa, N. *Chem. Lett.* **1992**, 473. (b) Iwasawa, N.; Matsuo, T. *Chem. Lett.* **1993**, 997. (c) Iwasawa, N.; Iwamoto, M. *Chem. Lett.* **1993**, 1257.

(50) (a) Kim, P.-J.; Hagihara, N. *Bull. Chem. Soc. Jpn.* **1965**, *38*, 2022. (b) Trifonov, L. S.; Orahovats, A. S.; Heimgartner, H. *Helv. Chim. Acta* **1987**, *70*, 1070. (c) Ahmar, M.; Antras, F.; Casez, B. *Tetrahedron Lett.* **1995**, *36*, 4417.

(51) Owada, Y.; Matsuo, T.; Iwasawa, I. *Tetrahedron* **1997**, *53*, 11069.

(52) (a) Trifonov, L. S.; Orahovats, A. S.; Trewo, R.; Heimgartner, H. *Helv. Chim. Acta* **1988**, *71*, 551. (b) Sigman, M. S.; Kerr, C. E.; Eaton, B. E. *Organometallics* **1995**, *14*, 269. (c) Murakami, M.; Itami, K.; Ito, Y. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2691. (d) Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1996**, *118*, 11672.

(53) (a) Eaton, B. E.; Rollmann, B.; Kaduk, J. A. *J. Am. Chem. Soc.* **1992**, *114*, 6245. (b) Mandai, T.; Tsuji, J.; Tsujiguchi, Y. *J. Am. Chem. Soc.* **1993**, *115*, 5865. (c) Sigman, M. S.; Eaton, B. E. *J. Am. Chem. Soc.* **1996**, *118*, 11783. (d) Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 2950.

(54) (a) Siegel, H.; Hopf, H.; Germer, A,: Binger, P. *Chem. Ber.* **1978**, *111*, 3112. (b) Mandai, T.; Suzuki, S.; Ikawa, A.; Murakami, M.; Kawada, M.; Tsuji, J. *Tetrahedron Lett.* **1991**, *32*, 7687. (c) Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 7163.

(55) (a) Khusnutdinov, R. I.; Dzhemilev, U. M. *J. Organomet. Chem.* **1994**, *471*, 1. (b) Roth, W. R.; Schmidt, T.; Humbert, H. *Chem. Ber.* **1975,** *108*, 2171. (b) Minter, D. E.; Fonken, G. J. *Tetrahedron Lett.* **1977**, 1717. (c) Olson, L. P. Gajewski, J. J. *Tetrahedron Lett.* **1993**, *34*, 2895.

(56) Murakami, M.; Itami, K.; Ubukata, M.; Tsuji, I.; Ito, Y. *J. Org. Chem.* **1998**, *63*, 4.

(57) Hayashi, M.; Ohmatsu, T.; Meng, Y.-P.; Saigo, K. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 837.

(58) Wender, P. A.; Takahashi, H.; Witulski, B. *J. Am. Chem. Soc.* **1995**, *117*, 4720.

(59) (a) Heck, R. F. *Palladium Reagents in Organic Synthesis*; Academic Press: London, U.K., 1985. (b) Poli, G.; Giambastiani, G.; Heumann, A. *Tetrahedron* **2000**, *56*, 5959.

(60) (a) Dieck, H. A.; Heck, R. F. *J. Org. Chem.* **1975**, *40*, 1083. (b) Mitsudo, T.; Fischetti, W.; Heck, R. F. *J. Org. Chem.* **1984**, *49*, 1640.

(61) (a) *Metal-catalysed Cross-coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: Weinheim, Germany, 1997; p 49. (b) Suzuki, A. *Acc. Chem. Res.* **1982**, *15*, 187. (c) Miyaura, M.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457. (d) Shirakawa, E.; Hiyama, T. *J. Organomet. Chem.* **1999**, *576*, 169.

(62) (a) *Metal-catalysed Cross-coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: Weinheim, Germany, 1997; p 167. (b) Farina, V.; Krishnamurthy, V.; Scott, W. J. *Org. React.* **1997**, *50*, 1.

(63) *Organo-copper-reagents—a Practical Approach*; Taylor, R. J. K., Ed.; Oxford University Press: Oxford, U.K., 1994; p 217.

(64) (a) Yamamoto, Y.; Radhakrishnan, U. *Chem. Soc. Rev.* **1999**, *28*, 199. (b) Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A. *Chem. Rev.* **2000**, *100*, 3067.

(65) (a) Myers, A. G.; Kuo, E. Y.; Finney, N. S. *J. Am. Chem. Soc.* **1989**, *111*, 8057. (b) Myers, A. G.; Dragovich, P. S. *J. Am. Chem. Soc.* **1989**, *111*, 9130. (c) Nagata, R.; Yamanaka, H.; Okazaki, E.; Saito, I. *Tetrahedron Lett.* **1989**, *30*, 4995. (d) Nagata, R.; Yamanaka, H.; Murahashi, E.; Saito, I. *Tetrahedron Lett.* **1990**, *31*, 2907. (e) Nicolaou, K. C.; Maligres, P.; Shin, J.; de Leon, E.; Rideout, D. *J. Am. Chem. Soc.* **1990**, *112*, 7825. (f) Myers, A. G.; Dragovich, P. S.; Kuo, E. Y. *J. Am. Chem. Soc.* **1992**, *114*, 9369. (g) Wang, K. K. *Chem. Rev.* **1996**, *96*, 207.

(66) Dopico, P. G.; Finn, M. G. *Tetrahedron* **1999**, *55*, 29.

(67) (a) Hollis, R.; Hughes, L.; Bowry, V. W.; Ingold, K. U. *J. Org. Chem.* **1992**, *57*, 4284. (b) Beckwith, A. L. J.; Bowry, V. W. *J. Am. Chem. Soc.* **1994**, *116*, 2710.

(68) (a) Schmittel, M.; Strittmatter, M.; Kiau, S. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1843. (b) Schmittel, M.; Keller, M.; Kiau, S.; Strittmatter, M. *Chem. Eur. J.* **1997**, *3*, 807.

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