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Acetylenic cyclophanes: emerging carbon-rich compounds for molecular construction and practical applications

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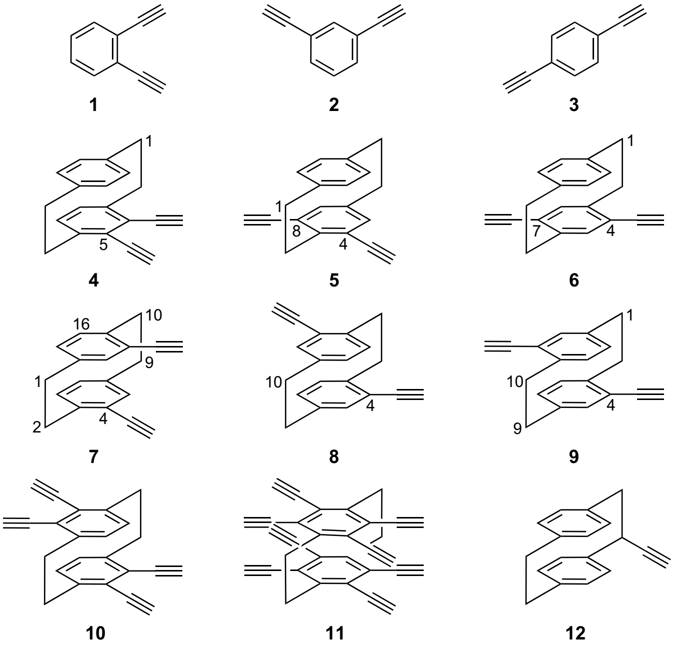
ABSTRACT

The preparation of simple acetylenic [2.2]parcyclophane 'building blocks' is described. These compounds are readily available from the commercially available [2.2]paracyclophane employing functionalization of the parent system and conversion of the resulting functional groups into triple bonds. For the incorporation of these structures into cyclophanes with 'extended' π-systems, coupling reactions such as the Sonogashira or the Glaser coupling are particularly valuable. Besides addition reactions the ethynyl cyclophanes can be employed to prepare novel iron, platinum, and cobalt metal complexes. By polycondensation reactions the monomeric cyclophanes can be converted into novel polymers displaying lateral π-conjugation. The application of alkynylcyclophanes in material science and nanochemistry is discussed.

1. Introduction

For the systematic preparation of novel carbon-rich compounds ('carbon rods' and 'carbon sheets') oligoethynyl benzene derivatives such as *ortho*- (**1**), *meta*- (**2**), and *para*-diethynyl-benzene (**3**) have turned out to be very useful building blocks allowing the introduction of angular (**1** and **2**: enclosed angles 60 and 120°, respectively) and linear (**3**) substructures into extended organic compounds and materials. In most cases the resulting oligomeric hydrocarbons are planar, but because of the free rotation around the single bonds connecting the aromatic ring and the triple bond three-dimensional objects are also possible, and have, indeed, been prepared.[1]

We propose to replace the benzene ring in **1**–**3** by a [2.2]paracyclophane unit. The carbon-rich compounds prepared from these *three-dimensional* building blocks will always be double-layered (and quite often chiral: see below) and should possess structural and electronic properties distinctly different from those resulting from the oligomers formed from **1**–**3**. The direct layered analogs of these benzene derivatives would be the diethynyl compounds 4,5- (**4**), 4,8- (**5**), and 4,7-diethynyl[2.2]paracyclophane (**6**). However, the cyclophane nucleus offers many more points of attachment of the triple bond as shown by the 4,12- (**7**), 4,13- (**8**), and 4,16-isomers (**9**) of the diethynyl derivatives (Scheme 1). Obviously more triple bonds can be introduced into the aromatic rings (see, for example, **10**) all the way to the octaethynyl derivative **11** in which all eight positions of the aromatic decks have been substituted. Taking into account that the eight ethano bridge positions can also carry triple bonds, derivative **12** represents a monosubstituted hydrocarbon of this type—a total of 16 hydrogen atoms can be replaced by either



Scheme 1. From classical aromatic acetylenes to ethynylparacyclophanes.

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unsubstituted or substituted/functionalized triple bonds. In a sense the cyclophane nucleus may be regarded as a hexadecavalent 'super atom', which can hold functionality pointing into clearly defined directions in three-dimensional space. Other such super atoms are conceivable—e.g., cubane, adamantane, C_{60}.

[2.2]Paracyclophane offers the advantages of combining two general types of reactive behavior: aromatic and aliphatic chemistry, allowing the application of numerous organic reactions to introduce the desired functionality. Triple bonds can also be part of the molecular bridges of an [*m*.*n*]cyclophane; however, these intermediates, that are very reactive when the bridges are short, will not be discussed in the present summary.

This overview of the alkynylcyclophanes begins with the preparation of the parent systems, and then proceeds to the synthesis of several derivatives and the use of these parent systems for the construction of extended structures ('molecular scaffolding'), and concludes with the presentation of several practical applications, especially from polymer chemistry, of these novel carbon-rich compounds.

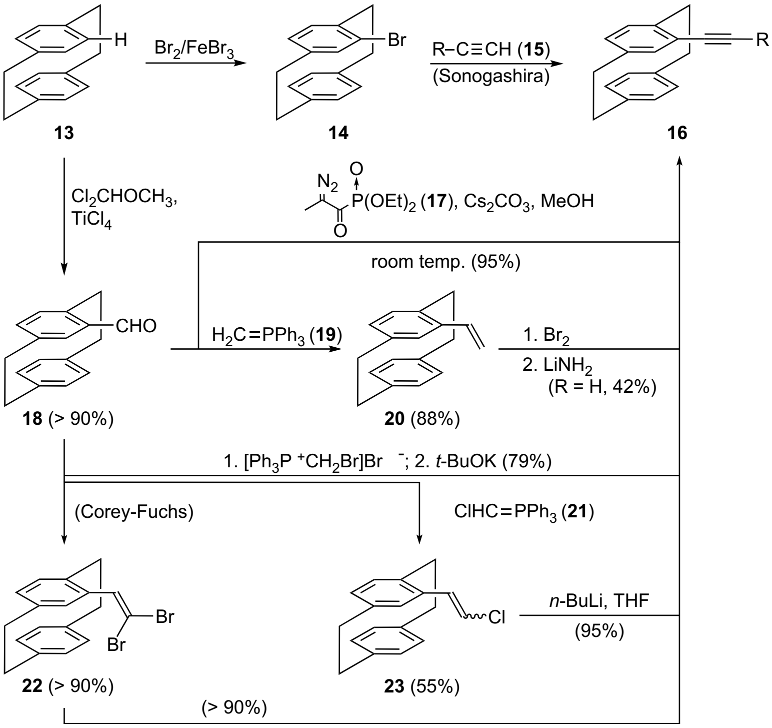
2. Preparation of the parent ethynyl[2.2]paracyclophanes

There are basically two modes to introduce a triple bond into a [2.2]parcyclophane framework: the triple bond is either introduced as a complete unit by a coupling reaction or it is prepared from a cyclophane carrying a carbon-containing functional group already by employing one of the standard methods of generating triple bonds. Scheme 2 summarizes these processes for the preparation of the parent system 4-ethynyl[2.2]paracyclophane (**16**, R=H):

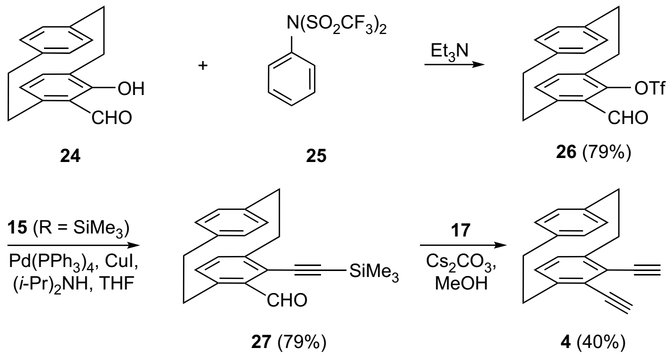
Electrophilic bromination of [2.2]paracyclophane (**13**) yielded the corresponding monobromide **14** in varying amounts; more highly brominated derivatives are always formed, and may, indeed, become the desired products when more highly substituted ethynylcyclophanes are required (see below). Sonogashira coupling of **14** ($Pd(PPh_3)_2Cl_2$, CuI, Et_3N, THF, PPh_3) with an appropriate acetylene **15** then provided the monoacetylenes **16**. For example, with trimethylsilylacetylene (**15**, R=$SiMe_3$) the cyclophane **16** (R=$SiMe_3$) was obtained in 90% yield; hydrolysis gave the parent hydrocarbon quantitatively.[2] The initial preparation of **16** (R=H) followed more conventional routes. Rieche formylation (Cl_2CHOCH_3, $TiCl_4$) of **13** furnished the 4-aldehyde **18** in more than 90% yield, and the subsequent Wittig olefination with ylide **19** led to the vinyl derivative **20** in 88% yield.[3,4] Dehydrogenation of **20** was accomplished by first adding bromine to the olefin, and then subjecting the resulting dibromide to elimination by lithium amide in liquid ammonia. Hydrocarbon **16** (R=H) was obtained in 42% yield.[3] In alternate chain extensions of **18** this was either reacted with diethyl-1-diazo-2-oxopropylphosphonate (**17**, Bestmann–Ohira reagent) in the presence of cesium carbonate (yield of **16**, R=H: 95%)[5] or treated with the chloro ylide **21**. The resulting vinyl chloride **23** (mixture of isomers) on *n*-butyl lithium treatment provided **16** (R=H) in 95% yield.[3] That the intermediate formation of a halide can be circumvented was shown by reacting **18** first with triphenyl bromomethyl phosphonium bromide and then adding potassium *tert*-butoxide in situ to the reacting mixture: **16** (R=H) was isolated in 79% yield in this case.[3] The most recent optimization of the **18**→**16** conversion involved a Corey–Fuchs reaction of the former derivative. Both steps, the preparation of the dibromide **22** from **18** (PPh_3, CBr_4, Zn, dichloromethane) and its double dehydrobromination (*n*-BuLi, THF, −78 °C) occur in excellent yield (>90%).[6] Today, **16** (R=H) is a building block easily available in multi-gram amounts.

Not surprisingly, the methods presented in Scheme 2 are also used in the majority of the syntheses of the higher ethynylated cyclophanes. As a matter of fact, the difficulty does not consist in the ultimate introduction of a triple bond, but in generating the substitution pattern desired for a specific alkynylcyclophane. This may be illustrated for five isomeric diethynyl[2.2]paracyclophanes.

As shown in Scheme 3 for the preparation of 4,5-diethynyl[2.2]paracyclophane (**4**) 5-formyl-4-hydroxy[2.2]paracyclophane (**24**, FHPC), a planar chiral salicylaldehyde[7] was employed as the starting material.



Scheme 2. Preparation of 4-alkynyl[2.2]paracyclophanes.



Scheme 3. Preparation of 4,5-diethynyl[2.2]paracyclophane (**4**).

In a first step, the OH-group of **24** was converted into a better leaving group by treatment with *N*,*N*-bis(trifluoromethylsulfonyl) aniline (**25**).[5] Into the resulting triflate **26**, the first triple bond was introduced by Sonogashira coupling and the second one with the Bestmann–Ohira reagent **17**. Deprotection took place during work-up and finally yielded the *ortho*-diacetylene **4**.

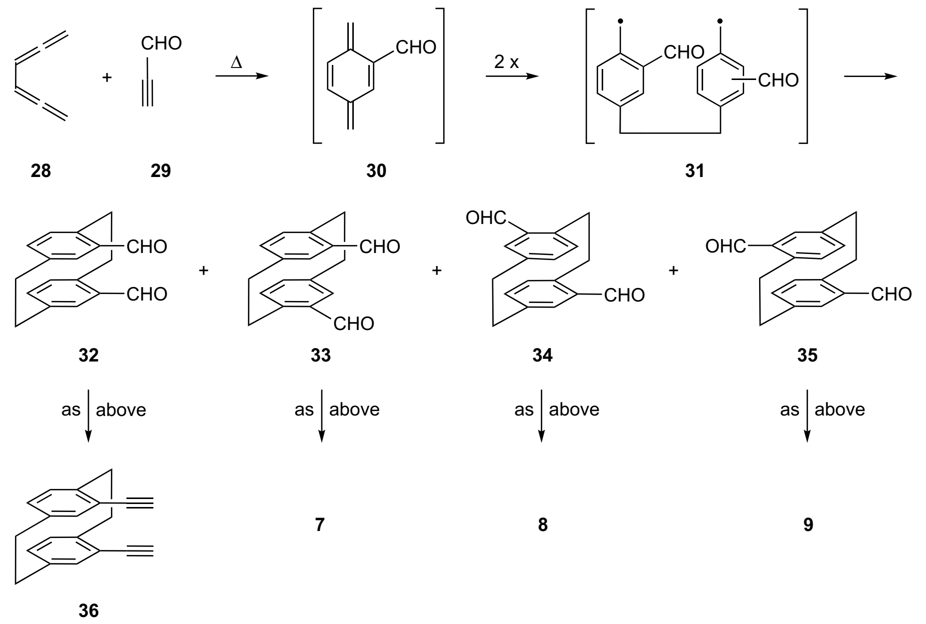
For the preparation of the four isomers **7**–**9** and **36** two general approaches have been reported. In the first route (Scheme 4) an isomeric mixture of the four dialdehydes **32**–**35** was prepared by the Diels–Alder addition of 1,2,4,5-hexatetraene (**28**) to propiolic aldehyde (**29**).[8]

The isomers are formed in about equal amounts in a total yield of ca. 50%, allowing the preparation of 50 g quantities in one cycloaddition experiment, thus off-setting to some extent the separation work (by recrystallization and column chromatography) required to obtain the isomerically pure dialdehydes. The four isomers are the expected ones, assuming that the reaction begins with the formation of the *p*-xylylene aldehyde **30** that subsequently dimerizes in a diradical process via intermediate **31**. The conversion of **32**–**35** by any of the routes discussed in Scheme 2 posed no problem.[5]

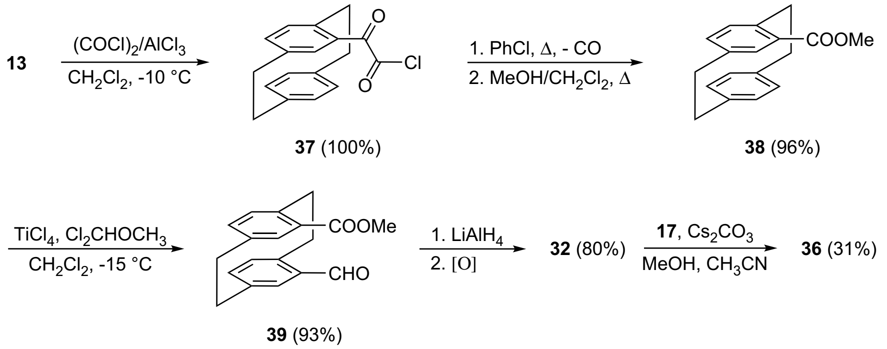
To obtain the diacetylenes **7**–**9** and **36** as the sole products of a synthetic sequence the development of specific routes is required.

For the pseudo-geminal diacetylene **36** the problem was solved as shown in Scheme 5.[9]

Friedel–Crafts acylation of [2.2]paracyclophane (**13**) with oxalyl chloride provided the keto acid chloride **37** in quantitative yield, which, by heating, followed by methanol treatment was converted in excellent yield into the methyl ester **38**.[10] The ensuing Rieche formylation exploited the pseudo-*gem* directing effect of electron-withdrawing substituents, discovered by Cram and Reich many years ago.[11] The formed ester aldehyde **39** was next reduced to the



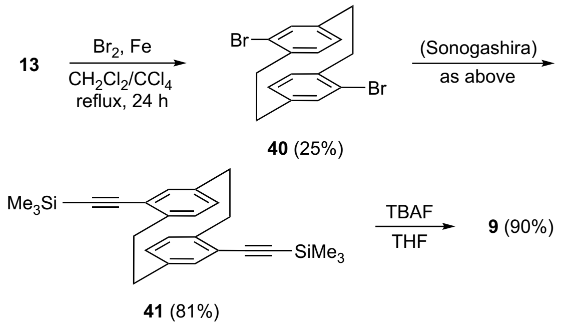
Scheme 4. [2.2]Paracyclophanes by Diels–Alder addition; conversion of aldehydes into acetylenes as described in Scheme 2.



Scheme 5. Preparation of pseudo-geminal diethynyl[2.2]paracyclophane (**36**).

corresponding bis diol, which was reoxidized (inter alia MnO_2, Swern oxidation, Dess–Martin oxidation) to **32**. In the last step this derivative was converted into **36** by treatment with **17**, the main product (61%) being the mono ethynylated derivative of **32**.[5]

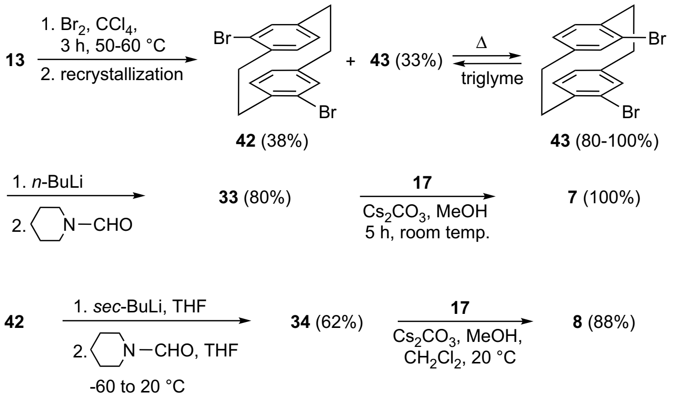
To prepare the pseudo-*para* isomer **9** Chujo and co-workers[12] subjected the parent hydrocarbon **13** to iron-catalyzed electrophilic dibromination according to a literature procedure,[13] and isolated the dibromide **40** after work-up and recrystallization in low yield (25%) as the sole product (Scheme 6).



Scheme 6. Preparation of pseudo-*para* diethynyl[2.2]paracyclophane (**9**).

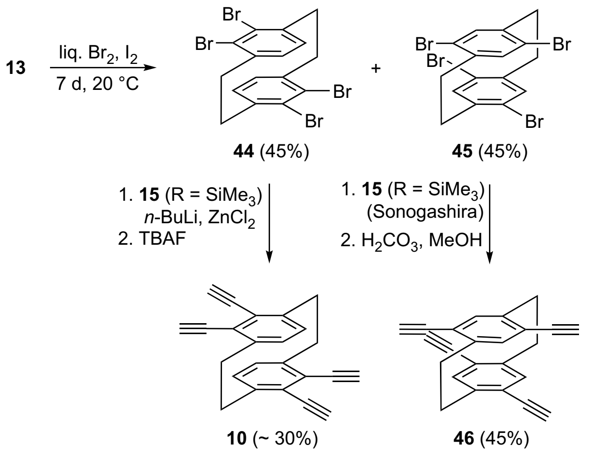
Sonogashira coupling as described above then yielded derivative **41** in good yield, which was deprotected by treatment with tetrabutylammmonium fluoride (TBAF) to the target molecule **9**.

Actually, the bromination of [2.2]paracyclophane (**13**) is a complex process and its outcome strongly depends on the reaction conditions. When the reaction was carried out under the conditions specified in Scheme 7[5] a mixture of the pseudo-*meta* (**42**) and pseudo-*para* dibromides (**40**) was produced in roughly 1:1 ratio. Because of their different solubility, these isomers can be separated by recrystallization from ethanol and dichloromethane easily. When **42** was heated to reflux in triglyme (216 °C), it equilibrated with the pseudo-*ortho* dibromide **43**, the product ratio being close to 1. After separation of **42** and **43**, the thermal equilibration process was repeated and after a third or fourth cycle practically all of **42** had been isomerized to **43**. Its metalation with *n*-BuLi in diethyl ether was next carried out and the formed dilithio derivative was quenched to the dialdehyde **33** with *N*-formyl piperidine in good yield. Conversion of **33** to the pseudo-*ortho* hydrocarbon **7** with **17** under the conditions given in Scheme 2 proceeded without any problems. Likewise the pseudo-*meta* dibromide **42** was converted into hydrocarbon **8**.[5]



Scheme 7. Preparation of pseudo-*ortho*- (**7**) and pseudo-*meta* diethynyl[2.2]paracyclophane (**8**).

Presently the most highly ethynylated [2.2]paracyclophanes seem to be the 'stepwise' hydrocarbon **10** and its 'crossed' isomer **46** (Scheme 8).



Scheme 8. Preparation of the 'stepped' and 'crossed' tetraethynyl[2.2]paracyclophanes **10** and **46**.

Their starting materials, the isomeric tetrabromides **44** and **45** were prepared by a procedure reported by de Meijere and co-workers; it involves the stirring of **13** in liquid bromine in the presence of iodine as a catalyst. After a full week of reaction time the two bromides were obtained in good yield in about 1:1 ratio. Again, their separation is readily possible because of different solubility in dichloromethane.[14] To prepare the target molecules **10** and **46**, respectively, from the dibromides, **44** was first metalated with *n*-butyl lithium and the resulting intermediate subsequently coupled with trimethylsilylacetylene (**15**, R=$SiMe_3$) in the presence of zinc chloride,[15] and **46** was obtained by Sonogashira coupling of **45** with **15** (R=$SiMe_3$).[16]

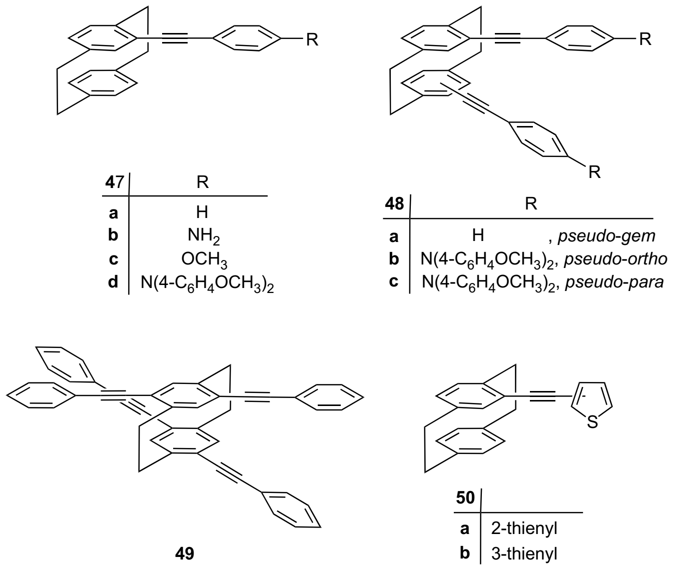
To prepare still more highly ethynylated derivatives of **13**—such as **11**—would demand the availability of paracyclophanyl halides beyond the above degree of substitution. It appears entirely feasible to prepare these substrates, since it should be possible to devise harsher reaction conditions than those presented in Scheme 8.

3. Preparation of substituted ethynyl[2.2]paracyclophanes

To introduce some order into the different types of ethynylparacyclophane derivatives, we propose to distinguish between 'simple' ethynyl[2.2]paracyclophanes and 'complex' structures obtained by 'molecular scaffolding', often by coupling of the simple building blocks. As simple derivatives the above parent systems would qualify as well as those consisting of only one cyclophane core or carrying substituents with only one triple bond. Obviously, a clean separation of 'simple' and 'complex' is impossible.

The number of simple derivatives of the above ethynyl[2.2]paracyclophanes is presently rather small. This is particularly true for ethynylcyclophanes carrying functional groups directly bonded to the triple bond, although these compounds should be easily available exploiting the acidity of the acetylenic hydrogen atom.[17] So far this position has most often been replaced by aromatic and heteroaromatic substituents. Examples are provided by the phenylethynyl derivatives **47a–d**, prepared by Sonogashira coupling of either **14** or **16** (R=H) and the respective coupling partners (Scheme 9).[18–20]

Likewise, 4,15-bis(phenylethynyl)[2.2]paracyclophane (**48a**) was obtained in 92% yield by connecting **36** with iodobenzene through Sonogashira coupling.[21] The pseudo-*para* isomer of **48a** is mentioned in a review on bichromophoric paracyclophanes,[22] and



47	R
a	H
b	NH_2
c	OCH_3
d	$N(4\text{-}C_6H_4OCH_3)_2$

48	R
a	H , *pseudo-gem*
b	$N(4\text{-}C_6H_4OCH_3)_2$, *pseudo-ortho*
c	$N(4\text{-}C_6H_4OCH_3)_2$, *pseudo-para*

50	
a	2-thienyl
b	3-thienyl

Scheme 9. Preparation of extended aromatic and heteroaromatic acetylenic [2.2]paracyclophanes.

both the pseudo-*ortho* and the pseudo-*para* bis tertiary amines, **48b** and **48c**, have been prepared by using the coupling protocols discussed above in a study investigating mixed-valence behavior in cyclophane radical cations.[20,23] For the tetra-substituted hydrocarbon 49, resulting from coupling of **45** with phenylacetylene, the isolated yield of 70% is excellent, considering that the same reaction had to be carried out four times.[14] Among the ethynylcyclophane derivatives carrying heteroaromatic substituents the two thiophenes **50a** (2-thienyl isomer)[6,24] and **50b** (3-thienyl isomer), both obtained in excellent yields by Pd/Cu-catalyzed Sonogashira coupling between 4-ethynyl[2.2]paracyclophane (**16**, R=H) and the appropriate hetaryl halides, are noteworthy. It is obvious that numerous other heteroaromatic groups can be introduced into these systems by a similar approach, yielding, for example, new ligands for the complexation of metal atoms or ions.

As examples of acetylenic cyclophanes carrying a functional group we quote **51**–**53** obtained from **16** (R=H) and the pseudo-geminal ester **39**[25] by standard organic reactions (Scheme 10):

Extension of **52** by coupling with 4-iodo-aniline (**54**) and 4-iodo-nitrobenzene (**55**), respectively, furnished the expected activated and deactivated phenylethynyl derivatives **56** and **57**, respectively, in good to quantitative yield.[26]

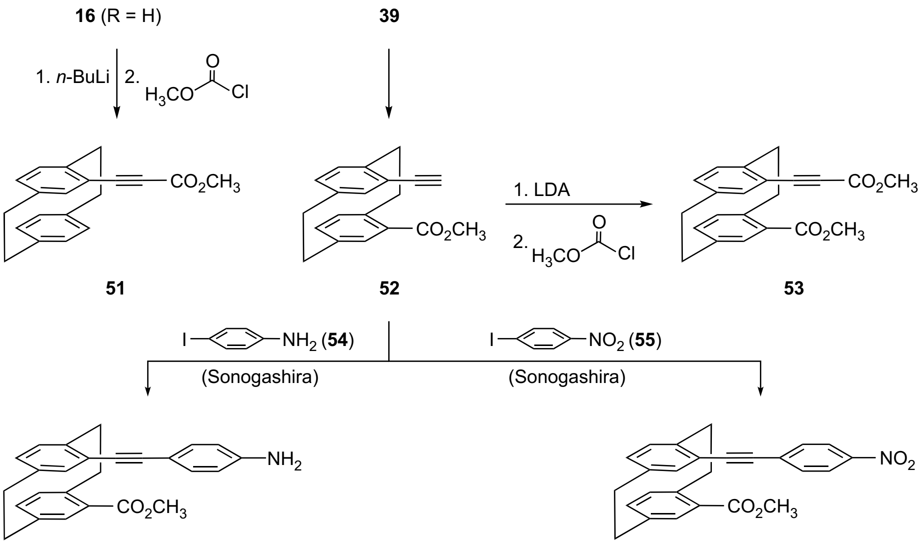
4. Employing acetylenic cyclophanes for molecular scaffolding

Cyclophanes that incorporate one or the other of the above ethynyl building blocks and which have overwhelmingly been prepared by employing oxidative coupling reactions using the terminal triple bond are beginning to attract more and more research activity. Typical examples for 'building' using **7**–**9**, **16**, and **36**, for example, are summarized in Scheme 11.[18,25]

The 'double' cyclophane **58** was formed in moderate yield when the monobromide **14** was treated with the monoacetylene **16** in the presence of a Pd catalyst. Because of the planar chirality of both paracyclophanyl substituents a *meso*- or a D,L-diastereomer could be formed in this process; although apparently only one product is generated in the coupling, the structural elucidation is incomplete in this respect so far. The diacetylene **61** was obtained in good yield by subjecting phenylacetylene (**59**) and the iodo-derivative of **16**, the cyclophane **60**, to a Cadiot–Chodkiewicz coupling reaction, again in the presence of a Pd catalyst. When this process was carried out with the diethynyl derivatives **7**–**9**, as well as **36**, now using the iodide **62** as the coupling partner, the bis(phenylbutadiynyl) derivatives **63** were produced in fair to good yield. Lambert and coworkers have described the tertiary amines derived from the pseudo-*ortho* and the pseudo-*para* isomers of **63**, with the substituents positioned in *para*-position as described in Scheme 9 for their lower ethynylogs.[20,23]

In all these (unoptimized) processes small amounts of mono-extended oligoethynylcyclophanes are produced, the hydrocarbons **64** and **66** being typical. Since these still possess a 'free' ethynyl group they can be oxidatively dimerized again; indeed, the 'stretched' hydrocarbon **65** and the 'layered' derivative **67** were obtained by the corresponding dimerizations (Scheme 12).[25]

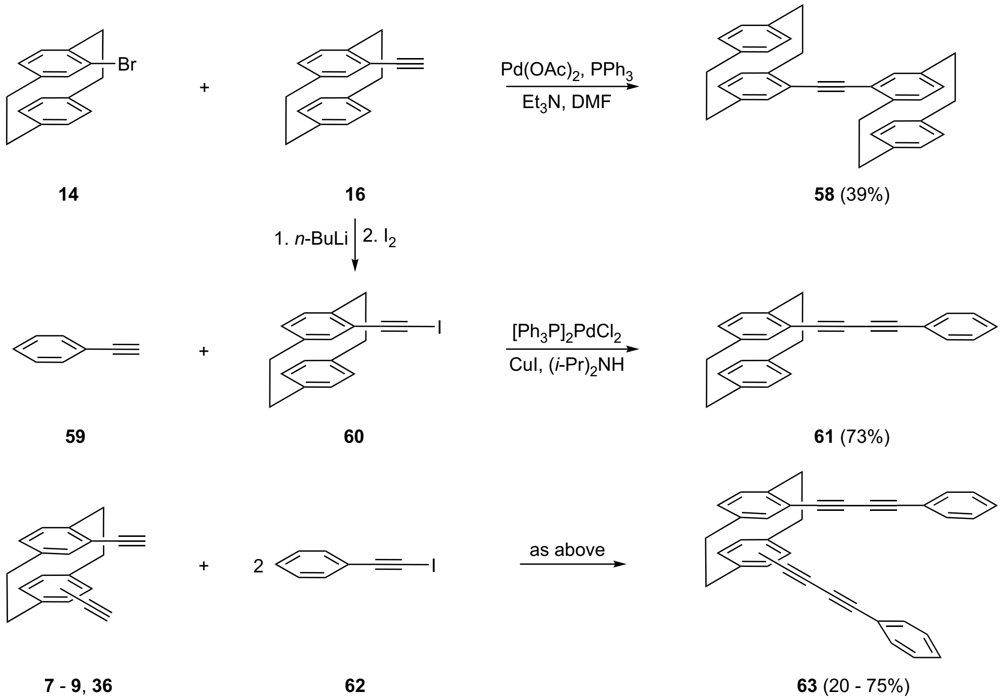
In the following examples (Scheme 13) the 'arms' of the ethynylcyclophanes are extended in a controlled way, indicating yet another time the enormous structural potential of these compounds for creating designed and novel arrangement of π-electrons in three-dimensional space.



51 **52** **53**

56 (60%) **57** (98%)

Scheme 10. Preparation of acetylenic [2.2]paracyclophanes carrying other functional groups.



Scheme 11. Molecular scaffolding with ethynyl[2.2]paracyclophanes.

Thus **16** (R=H) can be chain-elongated with either **68a**/**b** to the functionalized derivatives **69a**/**b** or coupled with the TMS-protected alkyne **70** to intermediate **71**. After this latter compound had been deprotected with TBAF to **72** this was coupled with the aryl iodide **73** to the cyclophane **74**, characterized by a very long oligo phenylethynyl arm (overall yield 46%).[27]

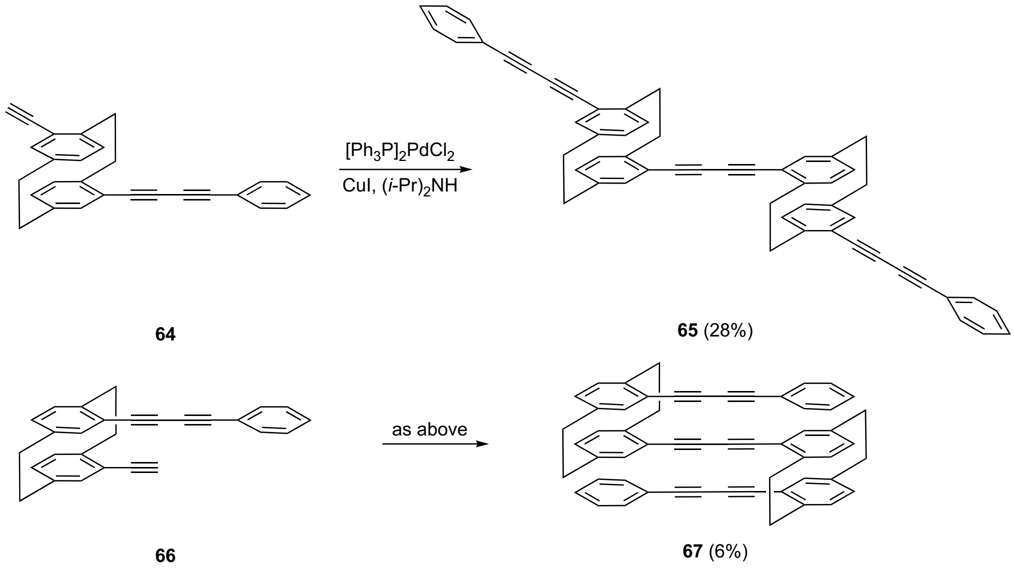
Further metal-mediated couplings allowed the preparation of derivatives incorporating thiophene rings in their substituents, **75**, **76a**/**b** (see below),[24] anthracene subunits, **77**,[28] or even metal containing moieties, allowing the preparation of redox-active polyiron complexes such as **78** (Scheme 14).[29]

A final selection of 'complex' examples is provided by the hydrocarbons assembled in Scheme 15. It is easy to discover the respective building blocks from Scheme 1 in these achiral (**79**, **81**, **83**) and chiral (**80**, **82**, **84**) structures.[30]

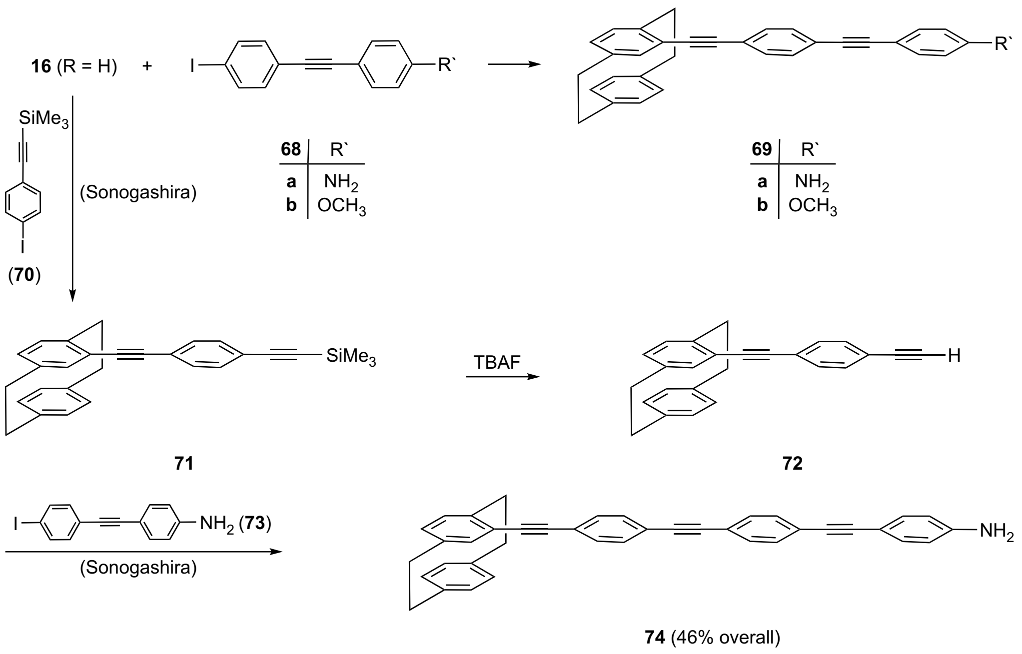
As a specific example, the preparation of **84a** from **46** might be discussed (Scheme 16), a propeller-type system that can be viewed as a double twisted annulene derivative.[31]

Sonogashira coupling of the 'crossed' tetraethynyl hydrocarbon **46** with aryl iodide **85** furnished the tetra-substituted derivative **86**, which was oxidatively cyclized to **84a** after its protecting trimethylsilyl groups had been removed by hydrolysis.

Some of these compounds, viz. **65** and **74**, look like space stations reduced to molecular dimensions. And, indeed, they are constructed by a similar approach, i.e., by interlinking of the respective 'modules'. Clearly, with a total of 16 positions available in



Scheme 12. Ethynylcyclophanes with very long arms.



Scheme 13. Even longer extended acetylenic [2.2]paracyclophanes.

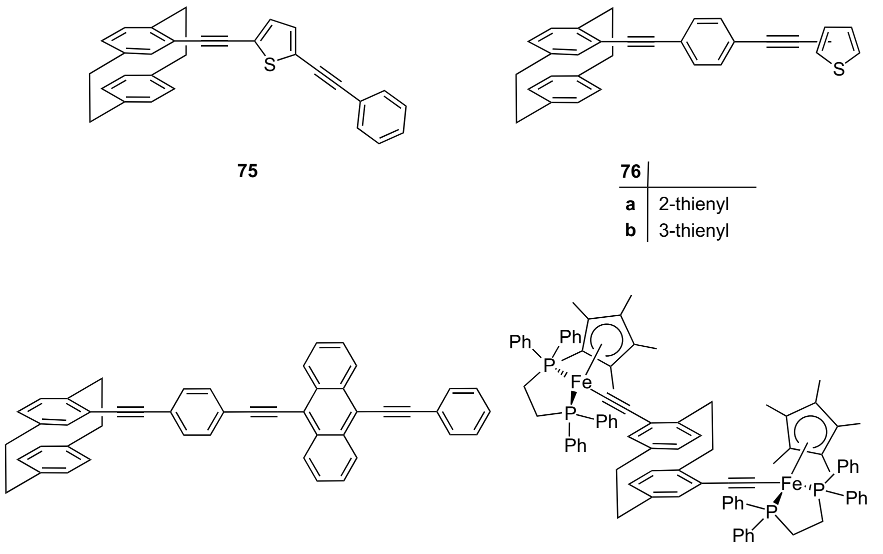
[2.2]paracyclophane (**13**) for 'docking', there exists an endless number of combinations to build these molecular satellites.

5. Reactions and applications of acetylenic cyclophanes

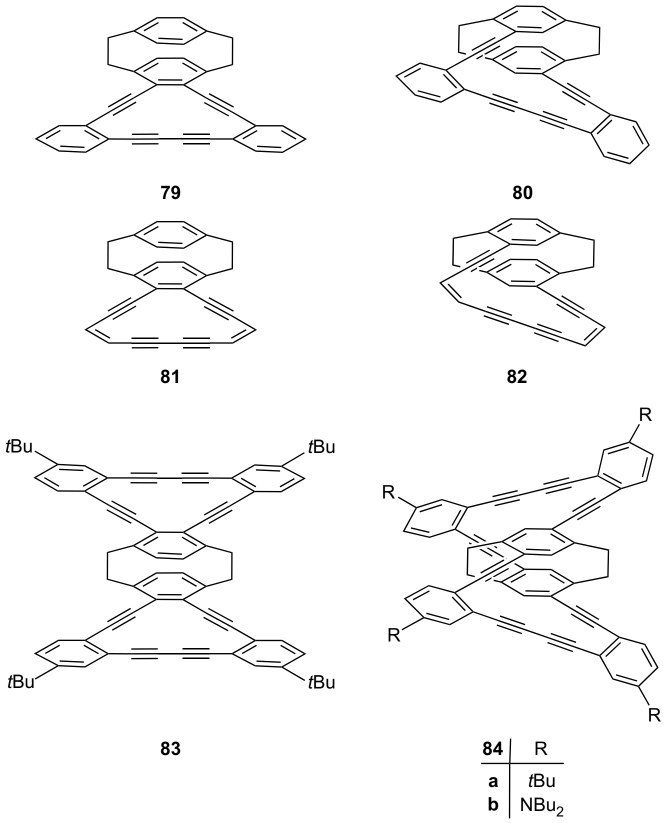
Several typical reactions of ethynylcyclophanes were encountered in the previous sections already; practically in all cases they involved the acetylenic hydrogen, i.e., its acidity or its propensity to participate in coupling reactions. The other large group of reactions of acetylenes involves addition processes, which can occur under a plethora of conditions (thermal, photochemical, acid-, base-, metal-catalyzed, etc.) by numerous mechanisms (concerted, ionic, radical, etc.). Since the chemistry of ethynylcyclophanes is a rather new area of investigation it is not surprising that there are hardly any systematic studies concerning their addition behavior. From the limited knowledge available, it can safely be predicted that a lot of synthetically and mechanistically interesting results can be expected in the near future.

A selection of addition reactions involving the simplest ethynyl[2.2]paracyclophane, the monoacetylene **16** (R=H), is presented in Scheme 17.

When dehydrobenzene (**87**), generated by the anthranilic acid route, was reacted with **16**, the latter functioned as a diene component and yielded the phenanthrenoparacyclophane **88** in acceptable yield.[32] Presumably the first step of this cycloaddition involves the generation of an isobenzene intermediate by a [2+4]cycloaddition,[33] which subsequently aromatizes by hydrogen migration. In contrast, with tetraphenylcyclopentadienone (**89**, tetracyclone) as the reaction partner, the triple bond of **16** functions as the dienophile, with the primary Diels–Alder adduct not



Scheme 14. Variations of substituents in acetylenic cyclophanes.



Scheme 15. Building complex three-dimensional molecular objects from ethynylcyclophanes.

surviving the rather harsh reaction conditions. The decarbonylated cycloadduct **90** was produced in very good yield (85%); various attempts to cyclize it to the layered polycyclic aromatic hydrocarbon **91** failed.[34]

Exposure of **16** to the catalytic influence of nickel 1,5,9-cyclododecatriene **92**, Ni(CDT), in toluene furnished the dimer **94** in poor yield (18%), most of the starting material (65%) being recovered.[3] With nickel bis(1,5-cyclooctadiene) (**93**) the results were similar, but now the hexadienyne **95** was produced as the main product.[3] No benzene derivatives were produced in both experiments as shown by NMR spectroscopy.

Among various derivatives of **16** (R=H) no substitution pattern has been studied more carefully than the pseudo-geminal one, since this allows the investigation of the interaction between functional groups not only in a fixed geometry but also in very close vicinity (ca. 300 pm), i.e., closer than the distance between the layers of graphite with 340 pm. A few pertinent examples are collected in Scheme 18.[35]

Thus the pseudo-geminal enyne **96** on irradiation with a high pressure mercury lamp formed the highly reactive anti-Bredt olefin **97** that on addition of 1,3-cyclopentadiene as a trapping agent furnished the Diels–Alder adduct **98**. Likewise the ethynyl aldehyde **99** was converted into the oxetene intermediate **100** that under the photolysis conditions was so reactive that it electrocyclically opened up to the α,β-unsaturated aldehyde **101**. As examples for ionic additions the reaction of **96** and **36**, respectively, with 1 equiv of bromine can be cited. In the former case the dibromide **102** was produced, whereas in the latter the diene **103** resulted. Both compounds were produced stereospecifically and very likely involve the intermediate generation of a bromonium ion that subsequently is trapped intramolecularly by the opposing ethynyl substituent.

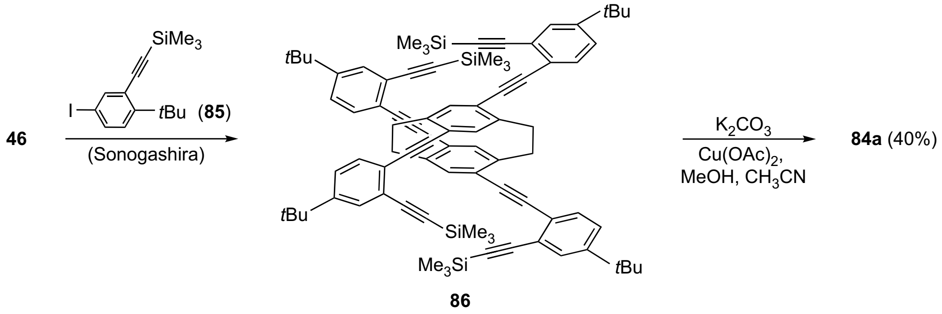
Although two parallel triple bonds in a pseudo-*gem* diacetylene could in principle give rise to a cyclobutadiene intermediate, there is so far only indirect evidence suggesting that this is actually taking place. As shown in Scheme 19 heating of the TMS-protected derivative **104** in the presence of iron pentacarbonyl in DME resulted in the formation of the cyclopentadiene complex **105**, formally a CO insertion product into the corresponding cyclobutadiene.[35]

Likewise, **48a** on irradiation furnished the two dimers **107** and **108**, two complex hydrocarbons, the formation of which can readily be explained by assuming that the cyclobutadiene **106** is generated as the primary intermediate.[21]

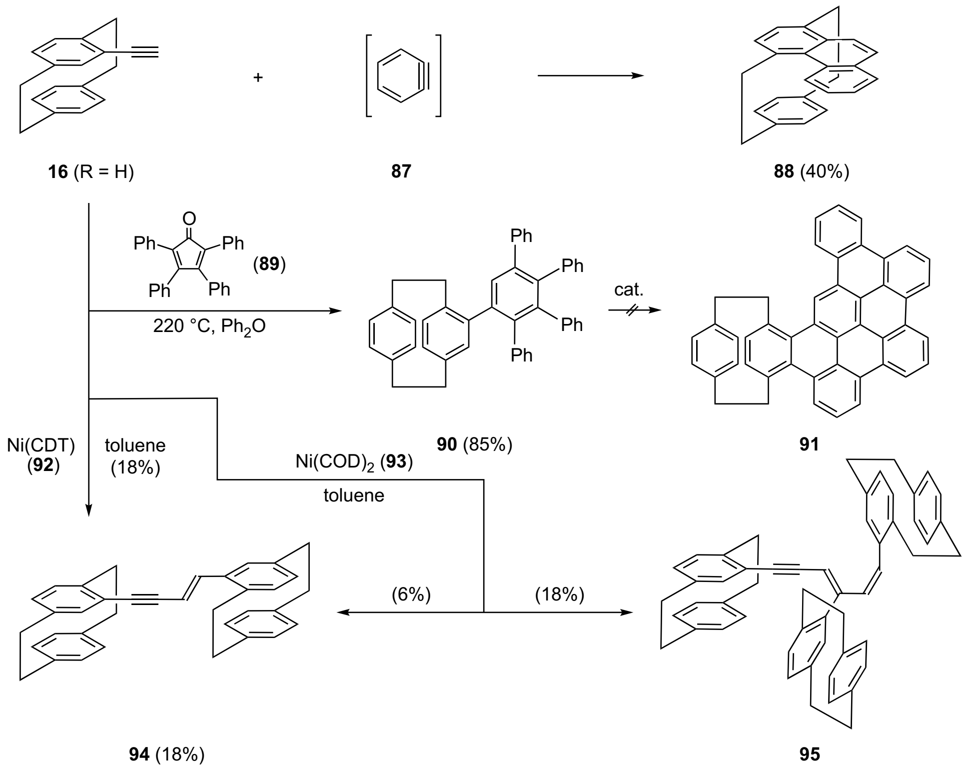
Novel metal complexes of ethynylcyclophanes were also produced by direct complexing of the triple bond or by an addition/carbonylation of it, as shown in Scheme 20 by the recently described metal complexes **109–111**, all obtained from the monoacetylene **16**.[6]

Another process showing the potential of polyacetylenic cyclophanes as substrates in organic synthesis is provided by the pseudo-*para* compound **112** (Scheme 21): on treatment with sodium sulfide hydrate it yields the bis thiophene **113** in good amounts thus providing an alternate route to heteroaromatically substituted cyclophanes (see above).[25] Another route of introducing sulfur into the substituents of alkynylcyclophanes exploits [2.3]sigmatropic rearrangements. However, because the triple bond is not bonded directly to the cyclophane core in these cases the corresponding examples are not dealt with in detail here for space reasons.[36]

On the other hand—and as expected—acetylenic cyclophanes with terminal triple bonds can be oxidatively dimerized using one of the classical acetylene coupling reactions such as the Glaser coupling. A case in point is provided by **16** (R=H), which yielded the dimer **114** on CuCl-mediated oxidation; as above in the case of **58** the exact stereochemistry (*meso* or D,L) of the butadiyne derivative has not been determined so far. This difficulty did not exist in the case of **7**, which under the same reaction conditions yielded the twisted dimer **115**, its structure having been determined by X-ray structural analysis.[37]



Scheme 16. The preparation of a double twisted annulene derivative.



Scheme 17. Selected addition reactions of 4-ethynyl[2.2]paracyclophane (**16**, R=H).

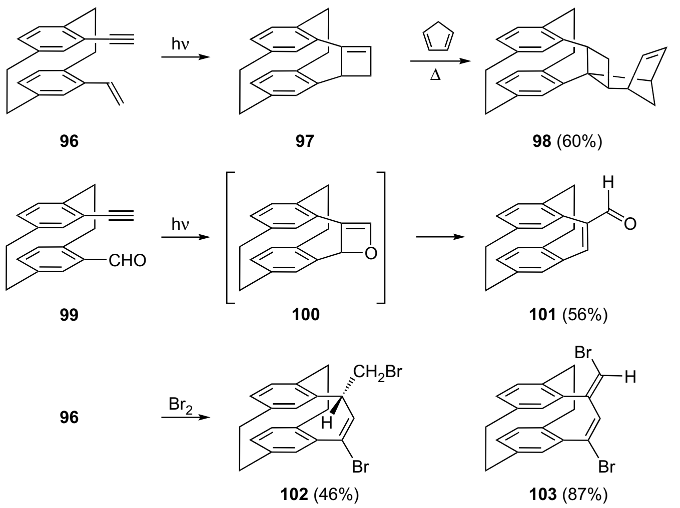
The above, still singular observations demonstrate the great potential that the acetylenic cyclophanes have for synthetic and/or structural chemistry, and it is likely that we will witness many new processes and products in this area in the not too distant future.

Another area where cyclophanes are becoming more and more popular is the vast field of new materials, whether it is the preparation of new polymers based on cyclophanes or the application of these compounds for the construction of new compounds with novel optical and electronic properties. The following examples are typical for ongoing research activities.

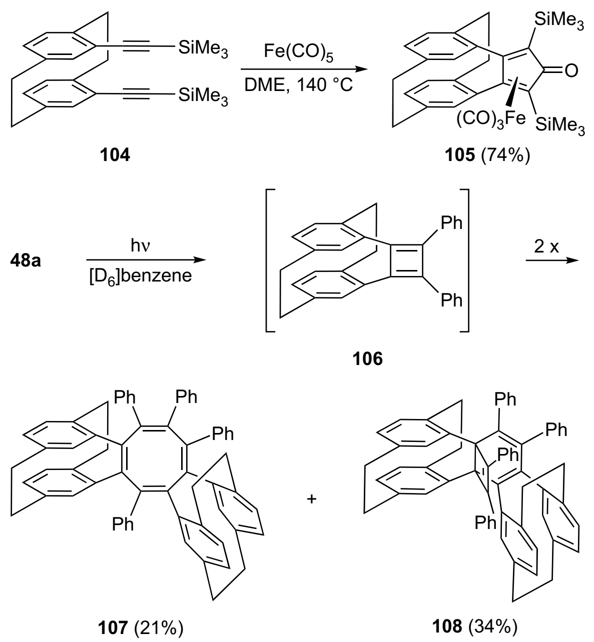
Ethynylcyclophanes have been used as building blocks for polymers in two different ways. In the first approach, the cyclophane moiety is kept intact in the polymer, and the transannular interaction between the aromatic 'decks' is employed for the transmission of electronic effects over long distances. In the second application the ethynylcyclophane is the only substrate and the phane core is destroyed by the polymerization process.

Scheme 22 presents several applications of the first approach, largely developed by Chujo and co-workers.

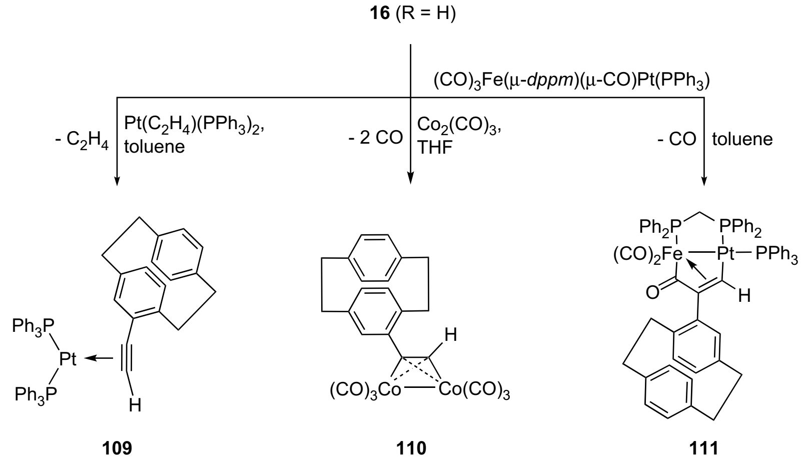
Initially the pseudo-*para* dibromide **40** was used as the starting material, which on coupling with the difunctional diacetylene **116**, carrying OAlk groups for solubilization, gave the polymers **117**,[38]



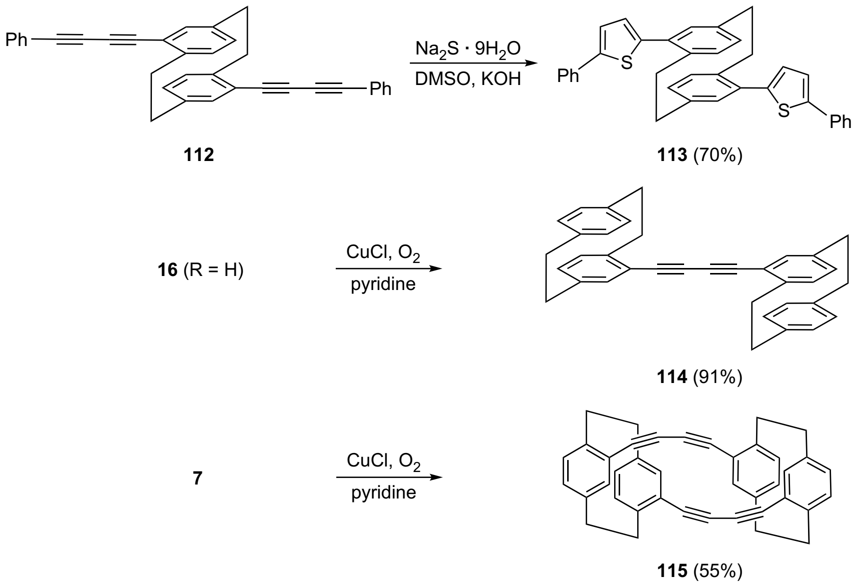
Scheme 18. Intramolecular interactions in pseudo-geminally substituted [2.2]paracyclophanes.



Scheme 19. Cyclobutadiene intermediates from pseudo-geminally substituted [2.2]paracyclophanes.

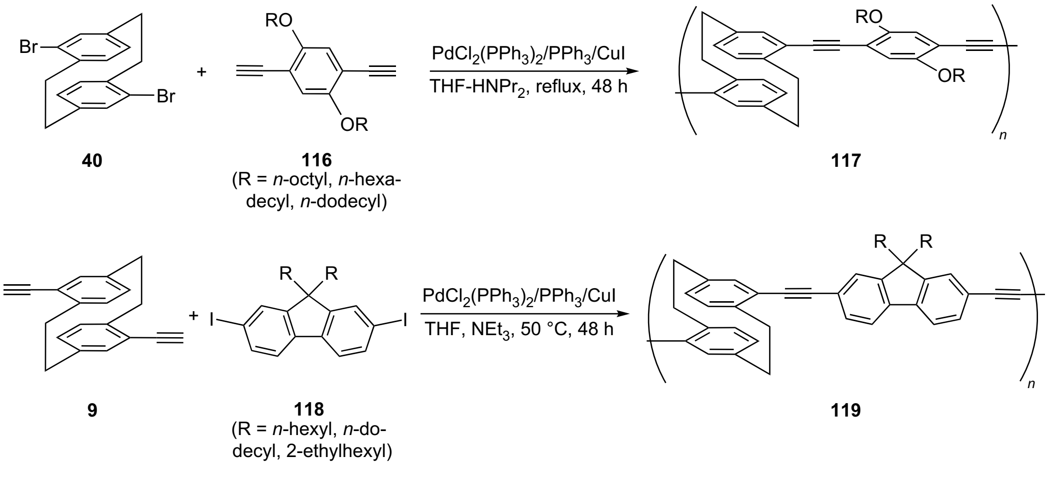


Scheme 20. New metal complexes from 4-ethynyl[2.2]paracyclophane (**16**, R=H).

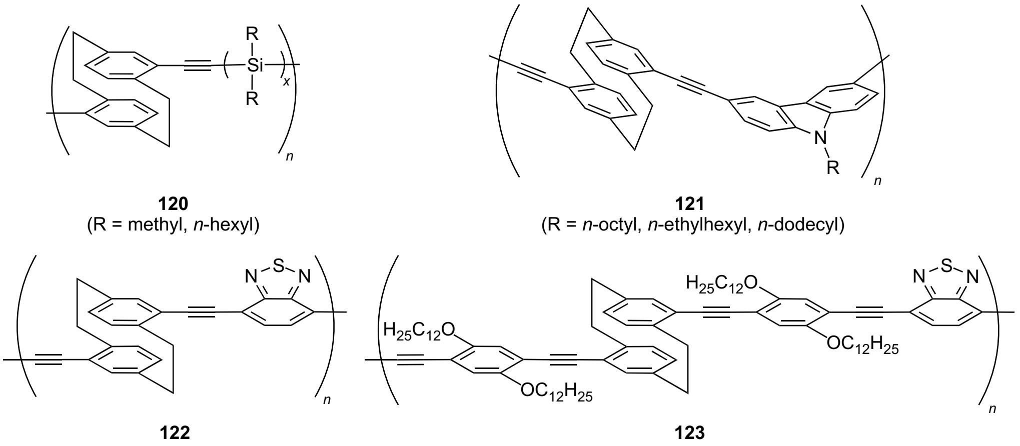


Scheme 21. Further addition and coupling reactions of acetylenic [2.2]paracyclophanes.

isolated in 70–98% yield as orange powders. For R=*n*-dodecyl the degree of polymerization corresponded to 11.5; the polymers were soluble in organic solvents such as THF, dichloromethane, chloroform, and toluene, but only partly soluble in DMF or acetone. In later experiments the cyclophane building block was replaced by the diethynyl derivative **9**, which could be coupled to numerous other bifunctional monomers, such as the 2,7-diiodofluorene derivatives **118**. The polymers **119** now obtained had a degree of poly-



Scheme 22. Incorporating [2.2]paracyclophane units into polymers: hydrocarbons.



120
(R = methyl, *n*-hexyl)

121
(R = *n*-octyl, *n*-ethylhexyl, *n*-dodecyl)

122

123

Scheme 23. Incorporating [2.2]paracyclophane units into polymers: heterorganic systems.

merization of 35, and displayed a strong blue fluorescence in solution and in the solid state,[39] making them attractive candidates for blue light-emitting materials with extreme photoluminescence and electroluminescence. With dichlorodisilanes and dichlorosilane, polymers of type **120** (Scheme 23) were obtained, which could be processed to a self-standing film by casting from a chloroform solution. The polymers showed delocalization of the π-electrons through the Si–Si bonds and through-space of the [2.2]paracyclophane moiety.[12,40] Analogously, [2.2]paracyclophane-containing π-conjugated polymers with a diacetylene unit (i.e., extended systems)[41] were prepared as well as those containing a carbazole subunit, **121**. Again, these polymers showed good thermal stability and displayed a strong blue photoluminescence in solution and bluish-green photoluminescence in the solid state.[42] The novel donor–acceptor type conjugated polymers **122** and **123** resulted from the Sonogashira coupling of 4,7-dibromo-2,1,3-benzothiadiazole with the appropriate dialkynyl[2.2]paracyclophane building blocks. The polymers could be processed by casting or spin-coating from a toluene solution to transparent and uniform films, and exhibited orange photoluminescence in solution and in the solid state. Thus, the color of these systems can be tuned by introduction of different aromatic buildings blocks into the main chain of the polymer.[43]

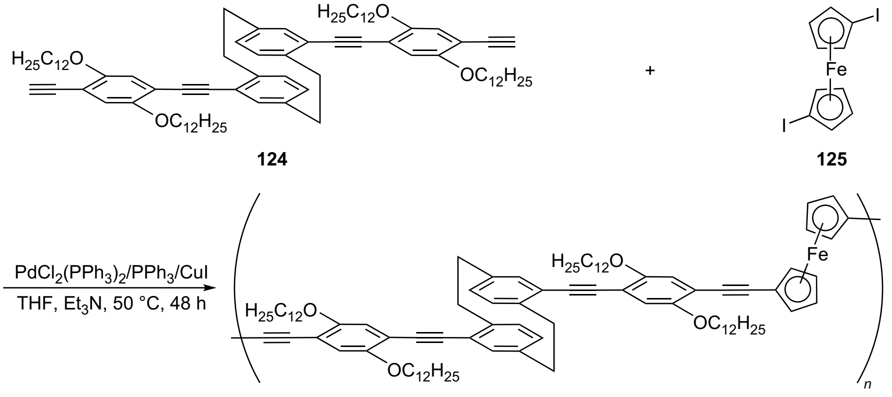
How far this type of 'molecular engineering' has advanced in the meantime is illustrated by the two examples assembled in Scheme 24 and Scheme 25. Here the two prototypes of layered molecules in organic chemistry, [2.2]paracyclophane, and organometallic chemistry, ferrocene, are combined in a deliberate fashion in polymeric superstructures.[44]

Reacting the paracyclophane **124** (obtained from **9** by a sequence of standard coupling steps) with 1,1′-diiodoferrocene (**125**) gave the expected polymer **126** in excellent yield. With a number-average molecular weight (M_n) of 24 500 this corresponds to a degree of polymerization of about 18. The polymers showed sufficient thermal stability and good film formation, making them promising candidates for application in electronic devices. Due to the presence of the iron atom the compound is redox active and on iodine doping under ambient conditions it showed electric conductivity.[45]

Finally, Pd-catalyzed polymerization of **9**, 2,7-di-*tert*-butyl-4,5-diiodo-9,9-dimethylxanthene (**127**), and ethynylferrocene (**128**) yielded the polymer **129**, which contained 7–30 face-to-face benzene rings, depending on the feed ratio of the starting materials **9**, **127**, and **128** (Scheme 25).[46]

The second route to the new polymers from ethynyl[2.2]paracyclophanes exploits the well-investigated Parylene® technology.[47] In the present case either the monoethynyl derivative **16** (R=H) or a mixture of the diethynyl[2.2]paracyclophanes **7**–**9** was pyrolyzed at 680 °C and 0.5 mbar (Scheme 26).[48]

During the pyrolysis process the ethano bridges of the starting cyclophanes are cleaved and the diradical pair **130** is produced (*p*-xylylene, *p*-quinodimethane). On cooling the corresponding vapor to 15 °C a Parylene® polymer is generated, which can be deposited on a surface, for example. In the case of **16** (R=H) a film, **131**, was

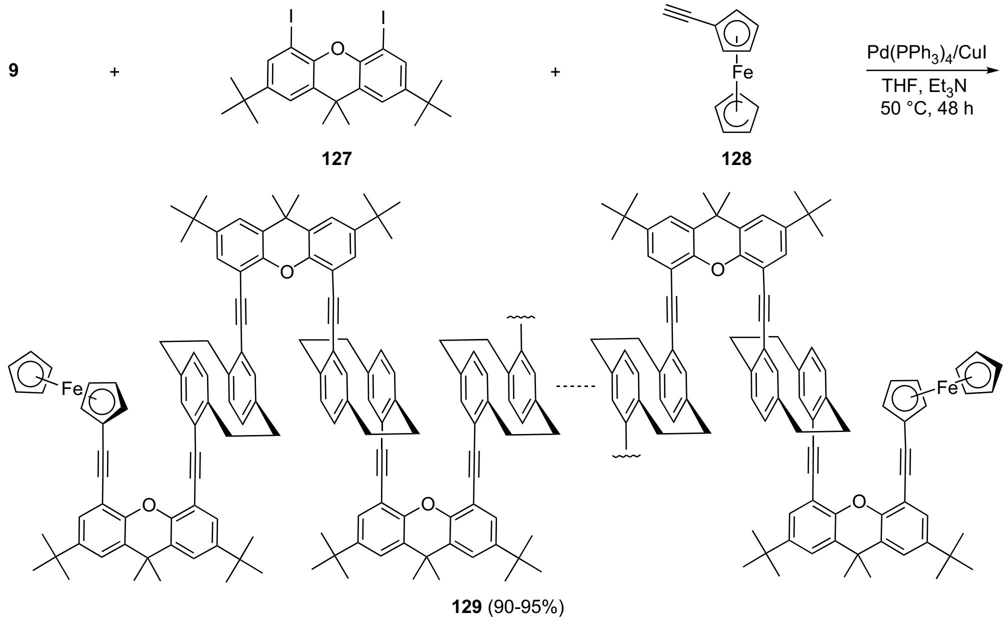


124

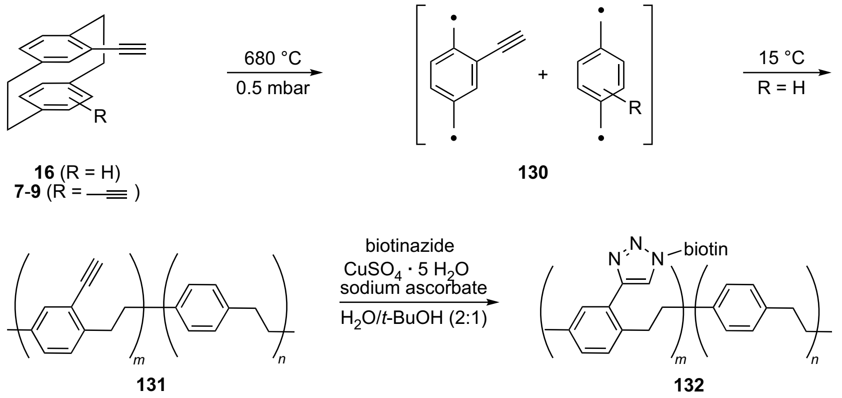
125

126 (93%)

Scheme 24. Polymers containing ferrocene and [2.2]paracyclophane subunits.



Scheme 25. Lateral π-electron overlap in very large systems.



Scheme 26. Creating bioactive surfaces with ethynyl[2.2]paracyclophanes.

produced that not only was stable at higher temperatures and toward solvents but also was still reactive enough to undergo a click reaction with biotinazide to produce the 1,3-dipolar adduct **132**. The resulting bioactive surfaces might find application in diagnosis (microarrays) or biosensing, for example.

Not only are polymeric materials derived from ethynylcyclophanes of interest in material science, but also some of the 'monomers' discussed above are beginning to be used in practical applications. Thus the two cyclophanes **74** and **77** containing acetylenic triple bonds in their linear 'side arms' have been used for the preparation of a variety of novel nanoscale materials in which it is important that all the building blocks are positioned in precisely defined geometries. When these compounds were incorporated as an electro active component within a conductive polymer such as poly(3-butylthiophene) a polymer blend was produced that displayed a photoelectrical response higher than that of the pure polymer.[49] In other applications these paracyclophane derivatives have been used to construct organic solar cells[28] and to create micron-scale ordered patterns on surfaces.[50–52] The iron complex **78** has been evaluated as a substrate for the preparation of a novel type of molecular wire.[29]

6. Conclusion

Acetylenic cyclophanes are carbon-rich compounds that can be prepared readily from the commercial product [2.2]paracyclophane (**13**) employing modern methods of metal-mediated C–C-bond formation. The resulting rigid 'building' blocks not only show interesting and important structural and chemical behavior themselves but also have been incorporated into 'extended' π-systems and polymers. It is to be expected that the number of these building blocks will increase quickly in the near future. A feature that so far has not been exploited in this area is the inherent (planar) chirality of many of these molecules. This could be used, for example, to synthesize novel chiral (and optically active) compounds that could be employed in many areas of chemistry, reaching from chiral ligands for stereoselective synthesis to chiral polymers for optical resolution.

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