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Syntéza kationových helikálních *N*-heterocyklů
Synthesis of cationic helical *N*-heterocycles

Diploma thesis

Supervisor: Prof. RNDr. Martin Kotora, CSc.

Prague, 2022

Prohlášení:

Prohlašuji, že jsem závěrečnou práci zpracoval samostatně a že jsem uvedl všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

V Praze, 26.08.2022

Podpis

Abstrakt

Diplomová práca sa zaoberá syntézou doposiaľ neznámych katiónových helikálnych heterocyklických zlúčenín pomocou katalytických procesov z jednoduchých stavebných blokov. Pozornosť bola zameraná na využitie katalytického štiepenia C–C väzby v bifenyléne s následnou anuláciou nitrilmi, metódou vyvinutou v našej výskumnej skupine. Ako alternatívny prístup bol zvolený Suzuki-Miyaura cross-coupling. Pripravené fenantridíny podliehali katalytickej C–H aktivácii s následnou anuláciou alkínmi za vzniku katiónových helikálnych heterocyklov. Pripravené látky majú potencionálne využitie v rôznych oblastiach materiálovej chémie.

Kľúčové slová: aktivácia C–C väzby, aktivácia C–H väzby, Suzuki-Miyaura cross-coupling, heterocykly, helikálne zlúčeniny, katalýza

Abstract

Diploma thesis concerns synthesis of hitherto unknown cationic helical heterocyclic compounds by catalytic processes from simple building blocks. The focus was on the utilization of a catalytic C–C bond cleavage in biphenylene followed by annulation with nitriles, a method that was developed in our research group. As an alternative approach was applied Suzuki-Miyaura cross-coupling. The prepared phenanthridines were used in catalytic C–H bond activation followed by annulation with alkynes giving rise to cationic helical heterocycles. These compounds have potential application in various fields of material chemistry.

Key words: C–C bond activation, C–H bond activation, Suzuki-Miyaura cross-coupling, heterocycles, helical compounds, catalysis

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Abbreviations

Ac	acetate
Bcl-xL	B-cell lymphoma-extra large
BDMIM	1-butyl-2,3-dimethyl-1H-imidazol-3-ium
BINAP	2,2'-bis(diphenylphosphino)-1,1'-binaphthyl
Bu	butyl
CFTR	cystic fibrosis transmembrane conductance regulator
COD	1,5-cyclooctadiene
Cp	cyclopentadiene
Cp*	pentamethylcyclopentadiene
DBU	1,8-diazabicyclo[5.4.0]undec-7-en
DCE	dichloroethane
DCM	dichloromethane
DDQ	2,3-dichloro-5,6-dicyano-1,4-benzoquinone
DMF	dimethylformamide
dppb	1,4-bis(diphenylphosphino)butane
dppe	1,4-bis(diphenylphosphino)ethane
dppp	1,4-bis(diphenylphosphino)propane
ESI	electrospray ionization
Et	ethyl
GSH	glutathione
L	ligand
M	metal
m-CPBA	*meta*-chloroperoxybenzoic acid
Me	methyl
Mes	mesityl
MW	microwave irradiation
NMR	nuclear magnetic resonance
Ph	phenyl
ppm	parts per million
R	alkyl
rt	room temperature

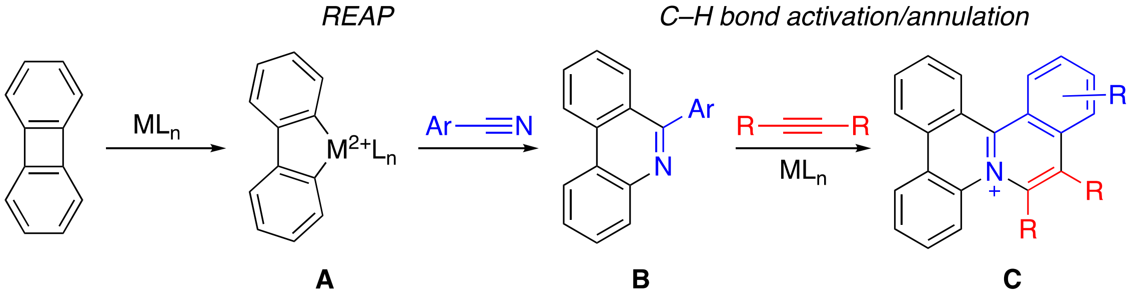
T	temperature
t	time
t-Am	2-methylbutan-2-yl
t-Bu	2-methylpropan-2-yl
TAA	thioacetic acid
Tf	trifluoromethanesulfonate
TFA	trifluoroacetic acid
THF	tetrahydrofurane
TIPS	triisopropylsilyl
TLC	thin layer chromatography
TMP	2,2,6,6-tetramethylpiperidine
TMS	trimethylsilyl
Ts	*para*-toluenesulfonyl
δ	chemical shift
v	repetancy

1. Introduction

Heterohelicenes are important group of molecules, which have been studied extensively ever since the discovery carbohelicenes. Carbohelicenes with unique helical backbone are interesting in the terms of their photophysical properties and, therefore, their applications are mainly in the fields of organic material chemistry. In order to enhance the photophysical properties of carbohelicenes, attention was focused on syntheses of heterohelicenes with various heteroatoms (N, P, S, O) and their effect on the above-mentioned properties.

For synthesis of heterohelicenes were developed various methods, such as oxidative photocyclization, [2+2+2] cyclotrimerization, and numerous coupling and cyclization methods. These methods are well established but require multistep synthesis of starting compounds.

During the work on my bachelor thesis, a synthesis of cationic *N*-heterocycles with the [4]helical scaffold was developed. The main advantage of this approach is a simple synthesis of starting compounds, phenanthridines **B**, by REAP (ring expansion annulation process) strategy. This step is followed by C–H bond activation/annulation sequence forming variously substituted cationic *N*-heterocycles **C** with the [4]helical scaffold (Scheme 1).



Scheme 1. Developed synthetic strategy towards cationic helical heterocycles with [4]helical scaffold.

The developed method is used for the synthesis of novel cationic helical *N*-heterocycles. As starting compounds for C–H bond activation/annulation will be used 6-substituted phenanthridines **B**.

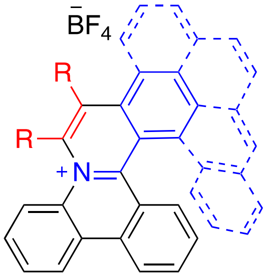
2. Aims of work

The thesis has the following objectives:

1. To develop the synthesis of new substituted phenanthridines with the focus on using catalytic C–C bond cleavage/annulation sequence.

2. To synthesize novel cationic helical *N*-heterocycles by catalytic C–H bond activation/annulation.

3. To measure photophysical properties of the prepared compounds, such as absorption and emission spectra, and to confirm the structure by single crystal X-ray analysis.

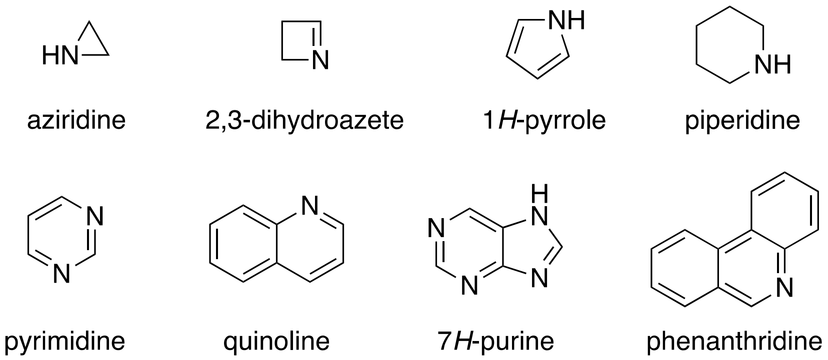


3. State of the art

3.1. *N*-heterocycles

Heterocycles are organic cyclic compounds with at least one heteroatom within their cyclic structures. Heteroatom can be any element other than carbon, but most known heterocycles contain phosphorus, oxygen, nitrogen, and sulphur. Structure can vary from three-membered rings up to nine-membered rings and even fused rings, with more than one heteroatom, and these compounds can have also aromatic properties. These compounds, or at least their structural motifs, can be found in nucleic acids, drugs, many of natural compounds and in synthetic dyes or have other interesting industrial applications. Thanks to numerous of applications, heterocyclic chemistry deals with classic problems, such as synthesis, application, and properties of these compounds.[1]

N-Heterocycles are heterocycles with the nitrogen atom as member of the ring structure and can form also aromatic molecules. Some examples of *N*-heterocycles are depicted in Figure 1.


aziridine 2,3-dihydroazete 1*H*-pyrrole piperidine

pyrimidine quinoline 7*H*-purine phenanthridine

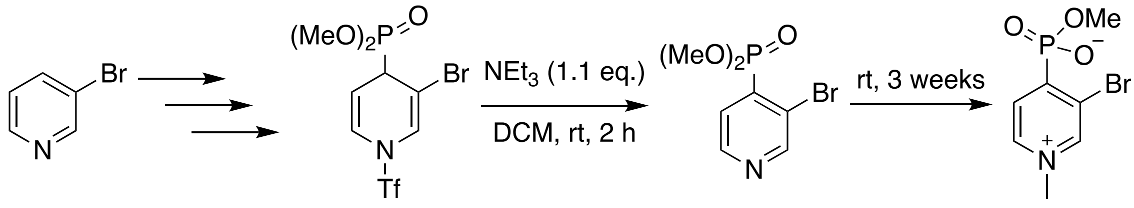
Figure 1. Examples of various *N*-heterocycles.

3.2. Cationic *N*-heterocycles

Cationic *N*-heterocycles are compounds with the positively charged nitrogen atom as a member of their ring structure. This class of organic compounds is recognized for its interesting properties in the fields of supramolecular chemistry, biologically active compounds, material chemistry, etc.[2] In this respect, the most interesting ones are those with fused rings. Their potential application has led to development of various synthetic routes to this class of compounds. In the field of bioactive compounds and pharmaceutical chemistry it is noteworthy to mention their antimalarial,[3] antileishmanial,[4] antiproliferative activity and DNA-intercalation,[5] as well as the ability to control CFTR activation.[6] Their bioactivity and other properties has led to the development of several approaches for syntheses of such cationic *N*-heterocycles.

3.2.1. Synthesis of cationic *N*-heterocycles by methods of classical organic chemistry

An interesting transformation forming cationic *N*-heterocycle was observed during the synthesis of *N*-heteroarylphosphonates. This type of compounds is well known for the ability to inhibit the corrosion of ferrous metals. In the first step of the synthesis, 3-bromopyridine (**1**) was transformed to phosphonate **2** and after base induced elimination of trifluoromethylsulfonic acid, phosphonate **3** was obtained. When compound **3** was kept at room temperature exposed to air, it was transformed to betaine **4** with cationic *N*-heterocycle framework (Scheme 2). This transformation was not observed when phosphonate **3** was kept under inert atmosphere in a freezer.[7]



1

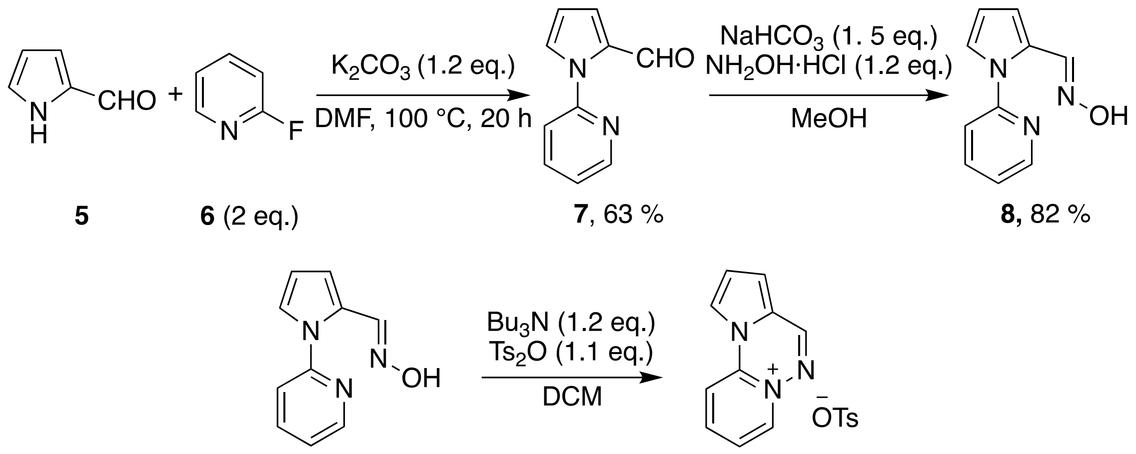
2

3, 70 %

4, 95 %

Scheme 2. Observed rearrangement with formation of cationic *N*-heterocycle **4**.

A simple strategy to prepare cationic triazinium heterocycles was reported in 2014. The synthetic route is based on a metal-free approach and simple reaction conditions. *N*-Arylation of 2-formylpyrrole (**5**) with 2-fluoropyridine (**6**) yielded aldehyde **7** that was transformed to oxime **8**. Finally, the N–N bond formation proceeded with formation of the desired product **9** (Scheme 3).[8]

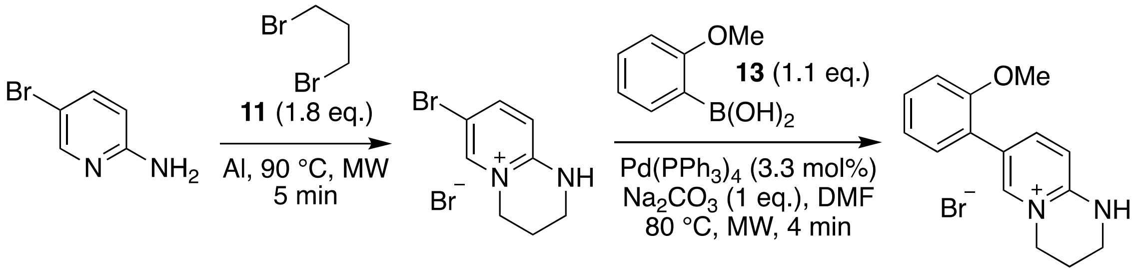


5 **6** (2 eq.) **7**, 63 % **8,** 82 %

8 **9**, 64 %

Scheme 3. Metal-free synthesis of triazinium heterocycle **9**.

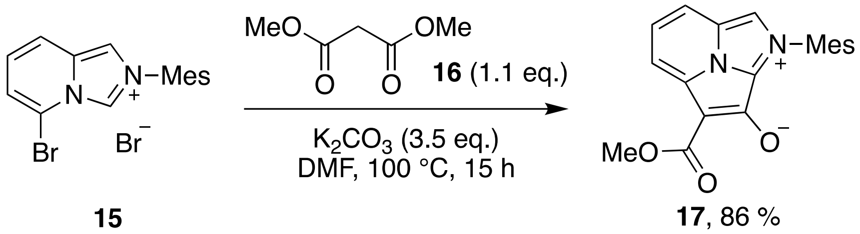
Syntheses of pyrido-fused tetrahydropyrimidiniums, diazepaniums and diazacaniums were based on a condensation reaction followed by Suzuki-Miyaura cross-coupling. An example of the synthesis is depicted in Scheme 4. The product **14** was prepared in two steps. The first step consisted of two-fold alkylation of bromo-2-aminopyridine (**10**) with dibromide **11** giving rise to a pyridinium salt **12**. The second step utilized Pd^0-catalysed Suzuki-Miyaura cross-coupling of **12** with an aryl boronic acid **13** under microwave irradiation to obtain the target compound **14**. The prepared pyridinium salt and its derivatives have potential application in pharmaceutical industry as drug precursors, and herbicids.[9]



10 **12**, 82 % **14**, 81 %

Scheme 4. Synthesis of pyrido-fused tetrahydropyrimidinium **14**.

A synthesis of mesoionic tricyclic *N*-heterocycles was accomplished by a single step nucleophilic aromatic substitution. As depicted in the example (Scheme 5), a reaction of methyl malonate **16** with a base formed malonate anion, which then reacted with imidazo[1,5-*a*]pyridinium **15**. In DMF, nucleophilic aromatic substitution was favoured and furnished product **17** in 86% isolated yield.[10]

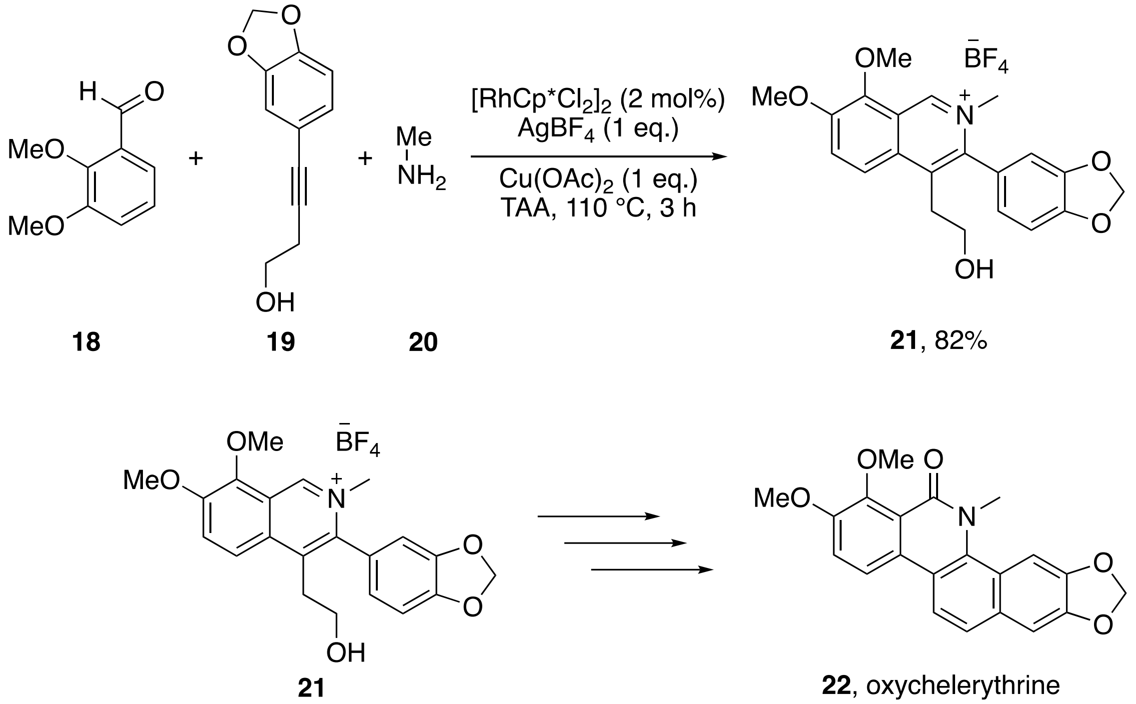


Scheme 5. Synthesis of mesoionic tricyclic *N*-heterocycle **17**.

3.2.2. Synthesis of cationic *N*-heterocycles catalysed by transition metal complexes

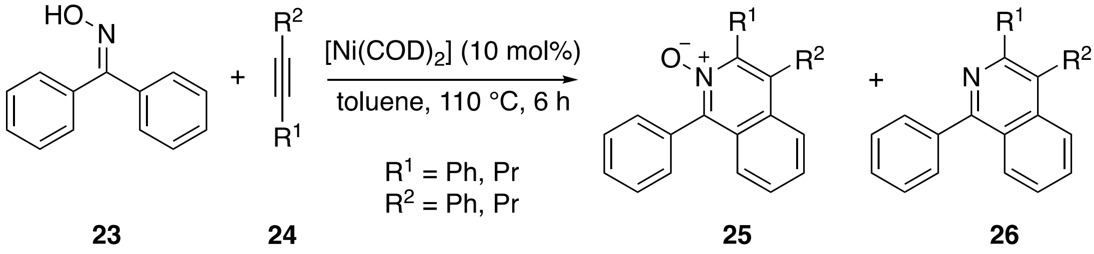
Development of new methods for the synthesis of cationic *N*-heterocycles has become an important task for metal-catalysed organic synthesis in recent years. The goal is to achieve preparation of highly substituted substances, which can act as intermediates in syntheses of natural compounds and bioactive molecules,[11] in synthetic organic chemistry in general,[12] or can be used as functional materials.[13]

One of the interesting applications of cationic *N*-heterocycle **21** is in the synthetic route towards oxychelerythrine **22**. This naturally occurring alkaloid has antitumor properties,[14] ability to inhibit BclXL function,[15] and stimulate GSH transport.[16] The first step of the synthesis is formation of an imine by a reaction of aldehyde **18** with methylamine (**20**), followed by C–H bond activation catalysed by a Rh^{III} complex and annulation with an alkyne to form isoquinolinium salt **21**. The synthesis of oxychelerythrine **22** was completed in 3 steps (Scheme 6).[17]



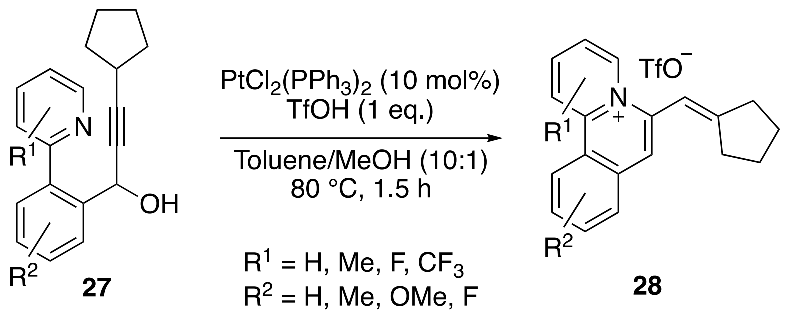
Scheme 6. Synthesis of oxychelerythrine **22** through isoquinolinium intermediate **21**.

Apart from a widely used C–H activation/annulation reaction sequence for the synthesis of azonia polycyclic compounds, other reaction pathways have been developed as well. One of them is [4+2] cycloaddition of aromatic ketoximes **23** and alkyne **24** catalysed by Ni^0 leading to isoquinoline *N*-oxides **25** with yields up to 60% and ratio 3/1 (**25**/**26**) (Scheme 7).[18]



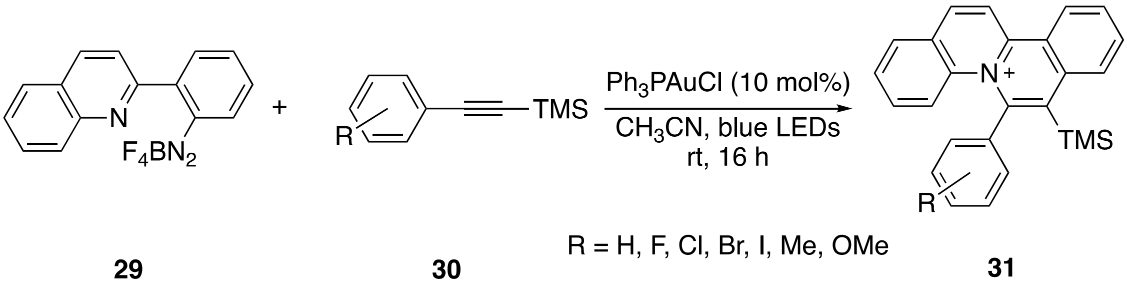
Scheme 7. Formation of isoquinoline *N*-oxides **25** through cycloaddtion.

Another structurally different cationic *N*-heterocycles, that are object of interest, are quinolizinium-type salts. These compounds can be used in material chemistry and can be prepared by Pt^{II} catalysed cyclization of propargyl alcohols **27** bearing the pyridine moiety (Scheme 8). The products **28** were synthesized with yields of 44–90%.[19]



Scheme 8. Synthesis of quinolizinium-type salts **28** through cyclization reaction.

Quinolizinium compounds bearing other functionalities apart from typical hydrocarbons and their derivatives, such as silyl groups, can be also synthesized. These compounds have been prepared, e.g., by photochemically induced radical Au^{I} catalysed *cis*-difunctionalization of alkynes **30** (Scheme 9). Compounds **31** were synthesized with yields up to 69% and have been tested out for potential use in cell imaging.[20]



Scheme 9. Synthesis of silyl derivatives of quinolizinium compounds **31**.

3.3. Helical compounds

3.3.1. Helicenes and helical chirality

The first discovery of helical compounds in nature relates to well-known right-handed double helix in DNA and the α-helix in proteins.[21] This discovery has sparked interest in a search for other compounds possessing the helical arrangement and in the phenomenon of helical chirality.[22]

There are mainly 3 groups of compounds having helical scaffold: helicenes, heterohelicenes, and helicene-like molecules. [*n*]Helicenes are molecules consisting solely of *ortho*-fused aromatic rings. The repulsion between terminal aromatic rings makes them chiral molecules without stereogenic centre.[23] There are two possible stereoisomers of helicenes: the left-handed helix is denoted as *M*, the right-handed one is denoted as *P* (Figure 2). Configurational stability of a helical compound is crucial for separation of individual stereoisomers. It depends on a number of fused aromatic rings and also on substituents. Helicenes having 5 or more aromatic rings are configurationally stable and their respective racemization barriers start at 27 kcal·mol^{-1} or higher.[24]

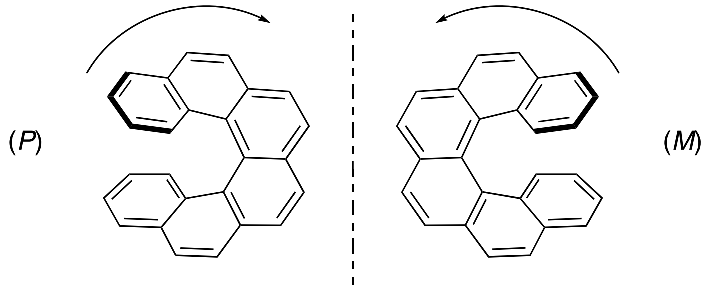


Figure 2. Two possible stereoisomers of hexahelicene.

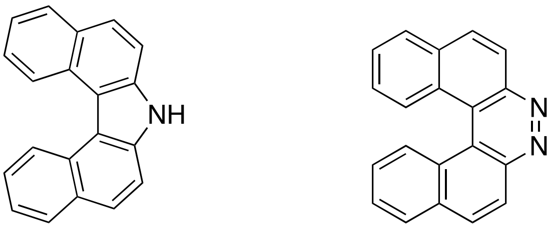
Other types of compounds with helical structure like heterohelicenes contain heteroatom within its aromatic structure, mainly nitrogen, oxygen, phosphorus, sulphur, and boron. Helicene-like compounds consist of at least one *ortho*-fused non-aromatic ring within their helical framework and are not fully aromatic.[25]

Helical structure and chirality of such compounds define their unique electronic and optical properties,[23] are connected with numerous of applications in asymmetric organo-catalysis,[26] transition metal catalysis,[27] materials science,[28] supramolecular chemistry, biology, and molecular recognition.[23]

3.3.2. Synthesis of azahelicenes

Since the discovery of helicenes, there has been growing interest in the synthesis of helicenes containing heteroatoms. The heteroatom in carbohelical backbone influences its chemico-physical properties and structure, therefore enlarge the area of applications of heterohelicenes. The main applications of heterohelicenes have been so far in spintronics, organic photovoltaics, organic field-effect transistors, and organic light-emitting diodes. Numerous of applications are the main reason for development of new synthetic routes towards heterohelicenes.[29]

One of the first attempts to synthesize a helical compound containing nitrogen atom(s) can be tracked back to 1903, when Meisenheimer and Witte tried to synthesize first two azahelicenes (Figure 3).[30]

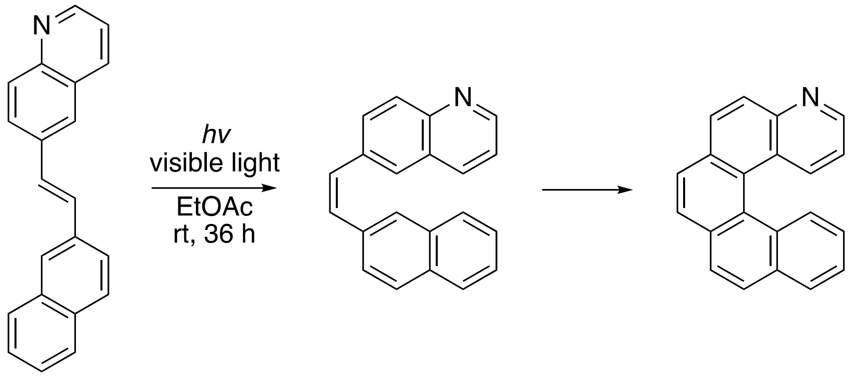


7*H*-dibenzo[*c*,*g*]carbazole benzo[*f*]naphtho[2,1-*c*]cinnoline

Figure 3. First aza[5]helicenes prepared in 1903.

During years various approaches have been developed in order to prepare new azahelicenes. The most common and simple method is oxidative photocyclization, but it has limitations regarding substrate structure. Moving on transition metal catalysis, wide range of reactions have been proved useful such as coupling reactions, [2+2+2] cyclotrimerization, and other cyclization processes. Thanks to availability of many synthetic routes, a wide range of azahelicenes has been prepared.[25]

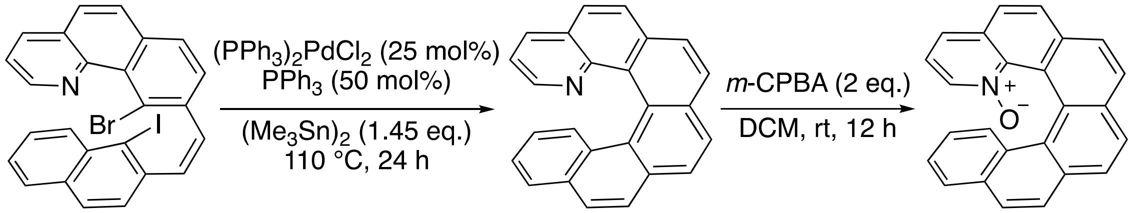
Oxidative photocyclization is generally well-known method for ring closure of 1,2-diarylethylenes. An example of this process is depicted in Scheme 10. (*E*)-Vinylquinoline **32** was exposed to visible light, which caused isomerization to (*Z*)-vinylquinoline **33**. Then the cyclization took place, and the final product 4-aza[5]helicene **34** was obtained in 47% yield.[31]



32 **33** **34**, 47%

Scheme 10. Oxidative photocyclization in the synthesis of aza[5]helicene **34**.

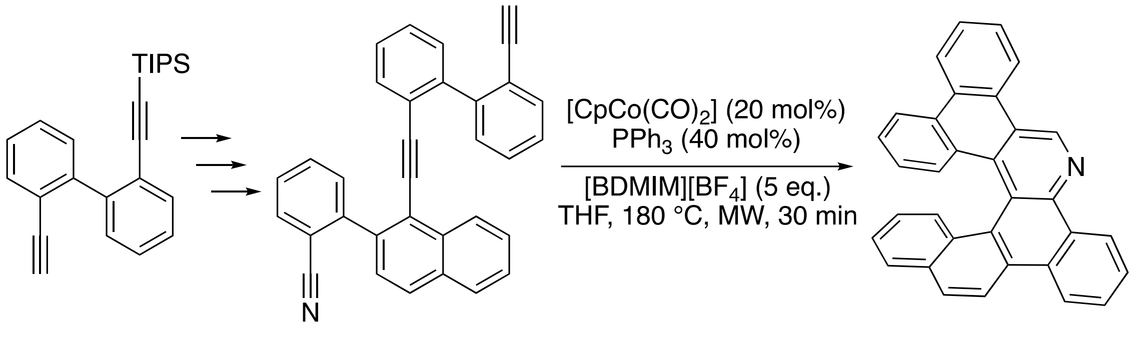
The use of the Stille-Kelly coupling allowed to synthesize azahelicenes in better yields and from easily available building blocks. In the synthesis of aza[6]helicene *N*-oxide **37**, the dihalogenated olefin **35** underwent the Stille-Kelly coupling to form aza[6]helicene **36**. The subsequent treatment of **36** with MCPBA furnished the product **37** in 32% isolated yield (Scheme 11).[32]



35 **36**, 61% **37**, 32%

Scheme 11. Stille-Kelly coupling in the synthesis of aza[6]helicene oxide **37**.

Catalytic [2+2+2] cyclotrimerizations are useful in the preparation of many helicenes including those with embedded nitrogen atoms. This methodology was used in a synthesis of pyrido[6]helicene **40**. Cyclotrimerization of cyanodiyne **39** was carried out using Ni^0, Co^I, or Rh^I complexes, but Co^I catalyst provided pyridohelicene **40** in the high 98% yield (Scheme 12).[33] The resulting compound has been tested for photonics,[34] thermopower,[35] and organocatalysis.[36]



38 **39** **40**, 98%

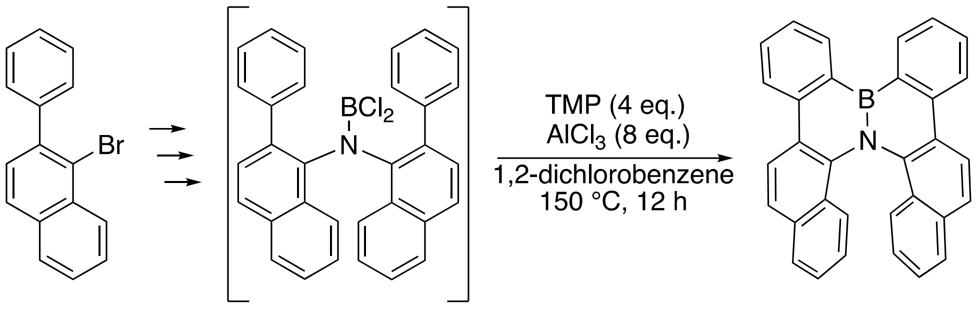
Scheme 12. Synthesis of pyrido[6]helicene **40** through [2+2+2] cyclotrimerization.

Another cyclization reaction includes a transition-metal-catalysed sequential intramolecular hydroarylation of alkynes. This reaction was reported in the synthesis of azahelical compound **42** (1-(phenylmethyl)benzo[*a*]naphtho[2,1-*k*]phenanthridin-2(1*H*)-one). The starting diyne **41** underwent cyclization reaction catalysed by a chiral Au^{I} catalyst, formed *in situ* by a reaction of Au^{I} complex with (*R*)-BINAP, and gave product **42** in 44% yield and 30% ee (Scheme 13).[37]

41 (*P*)-**42**, 44% yield, 30% ee

Scheme 13. Enantioselective synthesis of aza[6]helicene **42**.

A noteworthy reaction in the context of azahelicene synthesis is bora-Friedel-Crafts-type reaction. A synthesis of azaboradibenzo[6]helicene **45** was accomplished bz suing this transformation (Scheme 14). The substituted naphthalene **43** was transformed to compound **44**, which subsequently underwent intramolecular bora-Friedel-Crafts-type reaction. The azaboradibenzo[6]helicene **45** was prepared with 68% yield. Measurement of photophysical properties showed potential application of **45** in bipolar junction transistors and solar cells.[38]



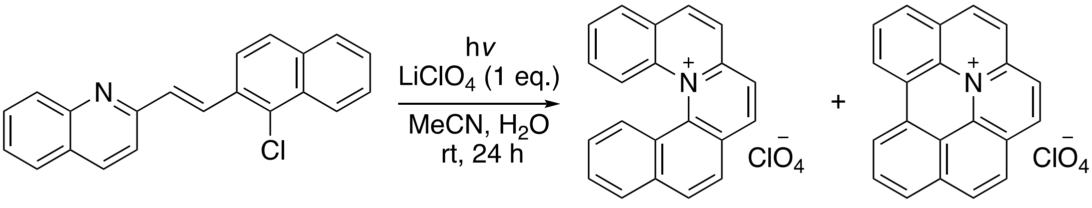
43 **44** **45**, 68%

Scheme 14. Synthesis of azaboradibenzo[6]helicene **45**.

3.3.3. Synthesis of azoniahelicenes

As opposed to azahelicenes, syntheses of azoniahelicenes have not received much attention. Only a limited number of azoniahelicens have been reported so far, although they promise to have a wide range of applications and interesting properties, which can be complementary to those of azahelicenes.[25]

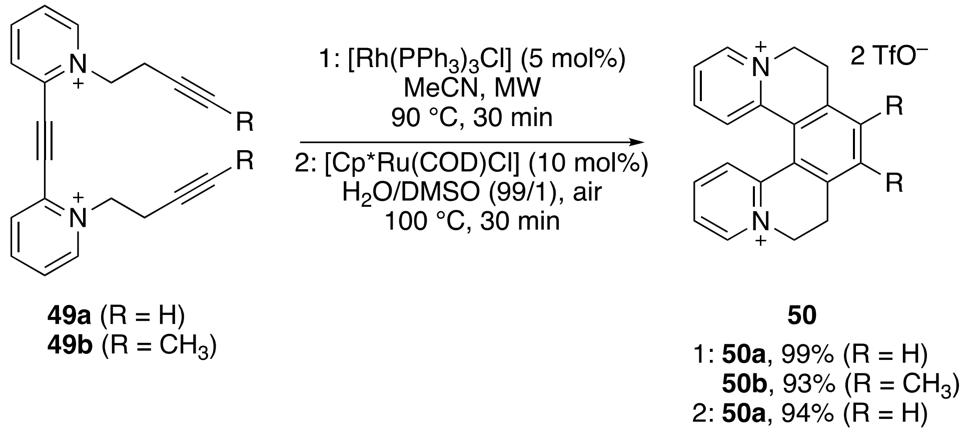
The first azoniahelicenes were synthesized using oxidative photocyclization reaction in 1998. As a typical example may serve photochemical cyclization of quinoline **46** under visible light and giving rise to a mixture of azoniahelicene (benzo[*c*]naphtho[1,2-*f*]quinolizinium) **47** and benzo[*kl*]quinolizino[3,4,5,6,7-*defg*]acridinium (**48**) as a by-product (Scheme 15).[39]



46 **47**, 15% **48**, 5%

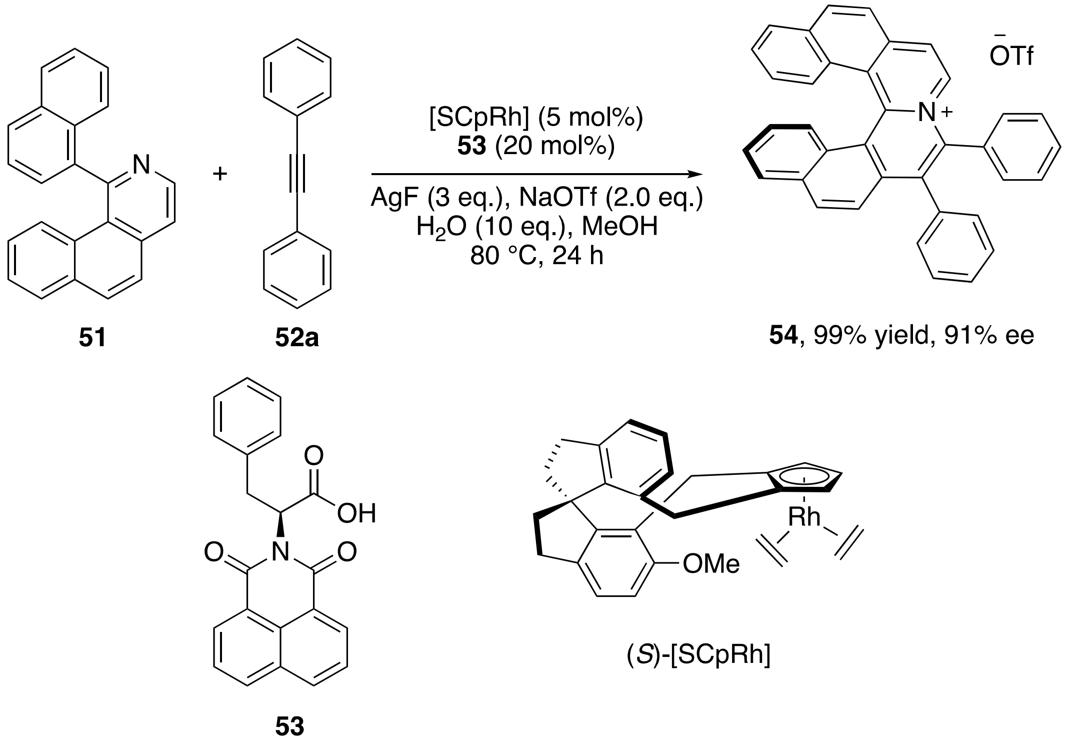
Scheme 15. First synthesized azoniahelicenes through oxidative cyclization.

Then in 2009, the first synthetic approach using [2+2+2] cyclotrimerization was reported for a synthesis of new class of compounds —helquats.[40] These azonia compounds are not fully aromatic and therefore are regarded as helicene-like molecules. The synthesis of [5]-, [6]- and [7]helquats was described by using this method. In the Scheme 16, there are depicted first synthesized [5]helquats **50**. A cyclotrimerization of dicationic triyne **49a** catalysed by Wilkinson's catalyst gave helquat **50a** in 99% yield. A reaction was also carried out using triyne **49b**, and helquat **50b** was prepared in 93% yield. For a cyclotrimerization of tryine **49a** was tested out another catalyst, a Ru^{II} complex. The reaction proceeded with 94% yield of helquat **50a**.



Scheme 16. First synthesized [5]helquats **50** using [2+2+2] cyclotrimerization.

Recently, a new approach for synthesis of new azoniahelicenes has been reported. It is based on a transition metal complex catalysed C–H bond activation followed by annulation with alkynes. The C–H activation is usually carried out by using cyclopentadienyl Rh complexes. Such a annulation reaction can be also carried out enantioselectively giving rise to enantioenriched azoniahelicenes. For example, a reaction of isoquinoline **51** with diphenylethyne (**52a**) catalysed by chiral (*S*)-[SCpRh] complex furnished cationic azoniahelicene **54** in 99% yield with high enantioselectivity of 91% (Scheme 17).[41]



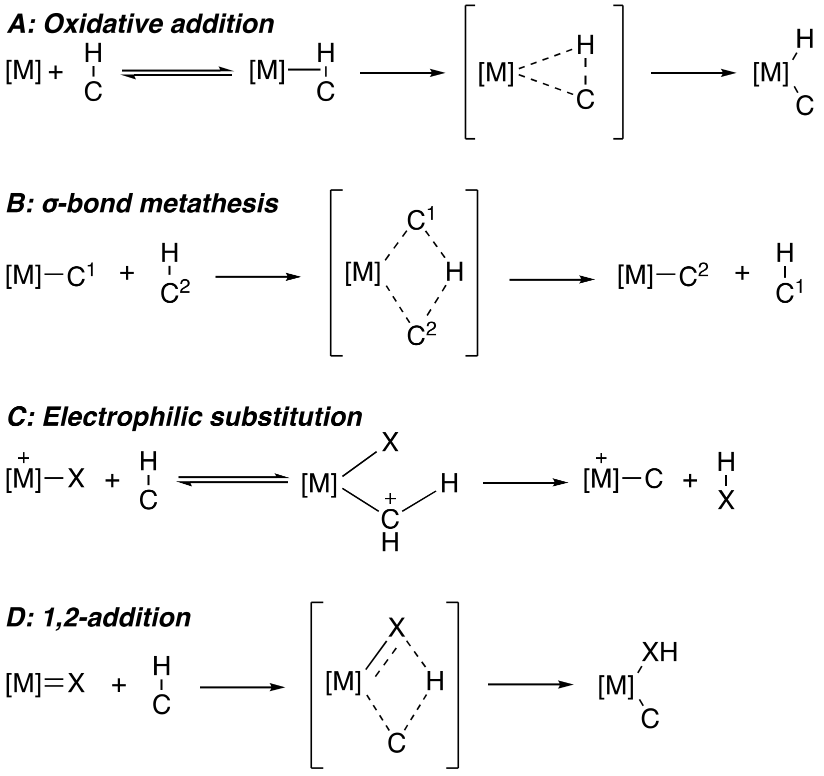
Scheme 17. C–H bond activation in the synthesis of azonia[6]helicene **54**.

3.4. C–H activation

The bonds between sp^3 or sp^2 carbon atoms and the hydrogen atom (C–H bond) are generally regarded in organic chemistry as highly unreactive functional groups, because of its high bonding energy (in the range from 372 kJ/mol for allylic C–H bond to 473 kJ/mol for phenyl CH bond).[42] The activation of such unreactive C–H bonds has become one of the major challenges in modern organic chemistry.[43] The major benefit of this approach is the use of unactive hydrocarbons as substrates and synthesis of various functionalized molecules without forming undesirable by-products. Therefore, a selective C–H bond activation has the potential to become the most powerful and the most broadly applicable transformation in organic synthesis.[44]

3.4.1. Mechanism of C–H bond activation

The most efficient way to achieve successful C–H bond activation is to use transition metal complex catalysis. Depending on the nature of a transition metal (M) and a ligand (L) in catalytically active ML_n species, the C–H bond activation can proceed through four different mechanisms: oxidative addition (*A*), σ-bond metathesis (*B*), electrophilic substitution (*C*), or 1,2-addition (*D*) (Scheme 18).[45]



Scheme 18. Different mechanisms of C–H bond activation.

The most common mechanism of C–H bond activation is oxidative addition (Scheme 17, *A*). The mechanism starts with coordination of a metal ion to a C–H bond, followed by concomitant cleavage of the C–H bond while forming new M–C and M–H bonds. During the course of the reaction, the formal oxidation state of the complex increases by 2 units, and geometry of the complex changes to create space for two new σ-bonds formed. Oxidative addition is favoured by electron rich, low-valent complexes of Re,[46] Fe, Ru, Os, Rh, Ir,[47] Pd, Pt.[48]

Complexes of early transition metals (groups 3 and 4), lanthanides and actinides with d^0 electronic configuration can't activate C–H bond through oxidative addition. The favoured mechanism is σ-bond metathesis (Scheme 17, *B*) preferred by alkyl or hydride complexes of the above-mentioned transition metals. The main characteristics of this mechanism include formation of $M–C^2$ and $H–C^1$ bonds and breaking of $M–C^1$ and $H–C^2$ bonds via a cyclic transition state. The oxidation state of the transition metal does not change through the course of the reaction.[49]

Mechanism of C–H bond activation proceeding through electrophilic substitution is formally equivalent to σ-bond metathesis. Electrophilic substitution mechanism is typical for metal complexes of Pd^{II}, Pt^{II}, Pt^{IV} and Hg^{II}. The intermediate is formed by electrophilic attack of the metal (Scheme 17, *C*). The metal centre in the product is acting as a Lewis acid, therefore the reaction is classified as electrophilic substitution.[45]

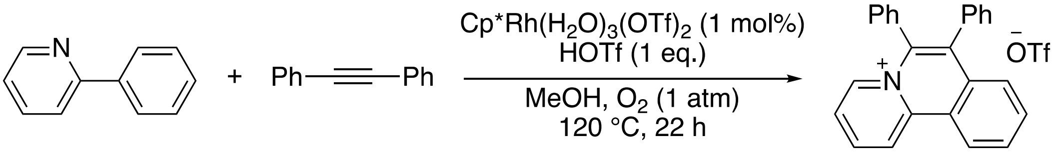
Activation of a C–H bond through 1,2-addition resembles σ-bond metathesis. The main difference is that the mechanism does not lead to release of HX, the M–X bond is still present in the product (Scheme 17, *D*). This reactivity was observed for complexes of various transition metals, where the functional group X represents amido or alkylidene groups. Alkoxy or alkylidyne complexes have also shown the ability to activate the C–H bond through 1,2-addition.[50]

3.4.2. C–H bond activation followed by annulation

Synthesis of cationic *N*-heterocycles using conventional methods consists of numerous steps and the necessity for pre-functionalization of starting material. On the contrary, transition metal-catalysed C–H annulation reactions are viable tools for step- and atom-economical organic synthesis of such compounds. The most often used catalysts for C–H bond activation/annulation are high-valent Cp*Rh^{III} complexes,[51] but also Ru^{II},[52] Cp*Ir^{III},[53] and Cp*Co^{III} complexes[54] have gained attention as prospective catalysts for such processes.

3.4.2.1. Mechanism of C–H annulation

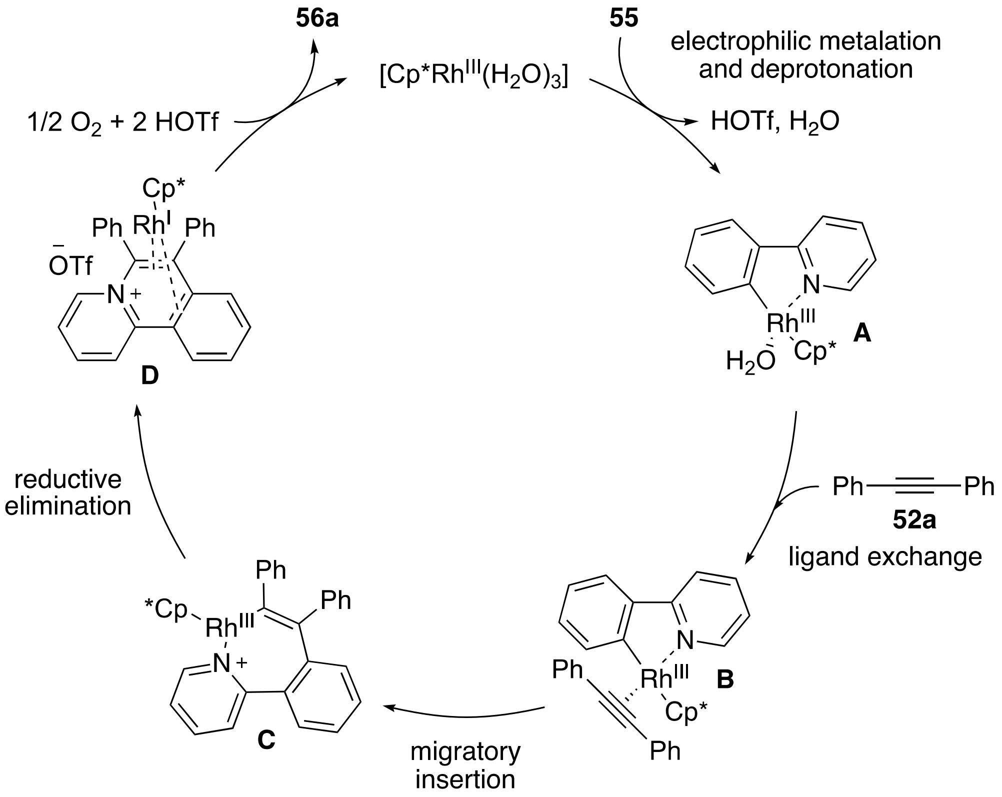
A mechanism of a rhodium complex catalysed C–H activation/annulation sequence, illustrated on the reaction of 2-phenylpyridine (**55**) with diphenylethyne (**52a**) (Scheme 19), is depicted in Scheme 20.[55]



55 **52a** **56a**, 99%

Scheme 19. C–H bond activation in 2-phenylpyridine (**55**).

The first step of the catalytic cycle is C–H bond activation in **55** through electrophilic metalation and deprotonation, forming the five-membered rhodacycle **A**. After ligand exchange to form complex **B**, migratory insertion of alkyne **52a** into the Rh-C bond gives the seven-membered intermediate **C**. Upon reductive elimination in **C** is formed complex **D**, in which the rhodium atom is coordinated to the aromatic π-system. Its subsequent reaction with oxygen releases product **56a** and the catalytically active species [Cp*Rh(H_2O)$_3$] is renewed.

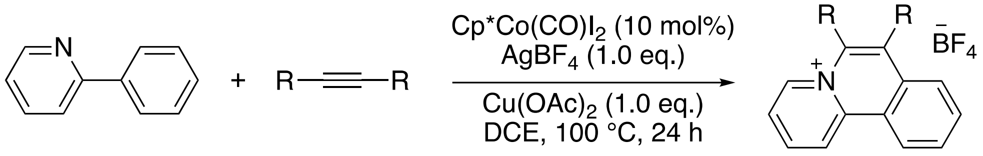


Scheme 20. Catalytic cycle of C–H bond activation followed by annulation.

3.4.2.2. Synthetic applications

The successfully developed C–H bond activation in 2-phenylpyridine (**55**) and annulation with alkynes **52** allowed the synthesis of series of pyridoisoquinolizinium salts **56** (Table 1).[56] The reaction was catalysed by $Cp^*Co^I(CO)I_2$, and $Cu(OAc)_2$ together with $AgBF_4$ as additives. The pyridoisoquinolizinium salts **56** were synthesized with yields up to 96%.

Table 1. Scope of the C–H annulation in 2-phenylpyridine (**55**).



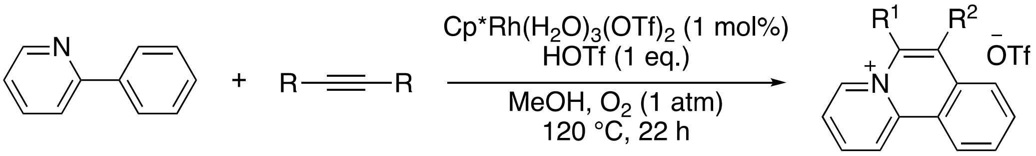
55 **52** **56**

Entry	**52**	R	**56**	Yield (%)[a]
1	**52a**	Ph	**56a**	96
2	**52b**	*p*-(*n*-Bu)C$_6$H$_4$	**56b**	74
3	**52c**	*p*-FC$_6$H$_4$	**56c**	90
4	**52d**	Et	**56d**	86
5	**52e**	2-thienyl	**56e**	23

[a] ^{1}H NMR yields.

The synthesis of the above mentioned pyridoisoquinolizinium salts **56** was slightly modified (simplified as far as the reaction conditions are concerned) in subsequent studies, but with the same outcome. As a catalyst was used a Rh^{III} complex and molecular oxygen was used as an oxidant instead of Cu(OAc)$_2$ (Table 2).[55] The reaction yields were up to 99%.

Table 2. Scope of the modified synthesis of pyridoisoquinolizinium salts **56**.



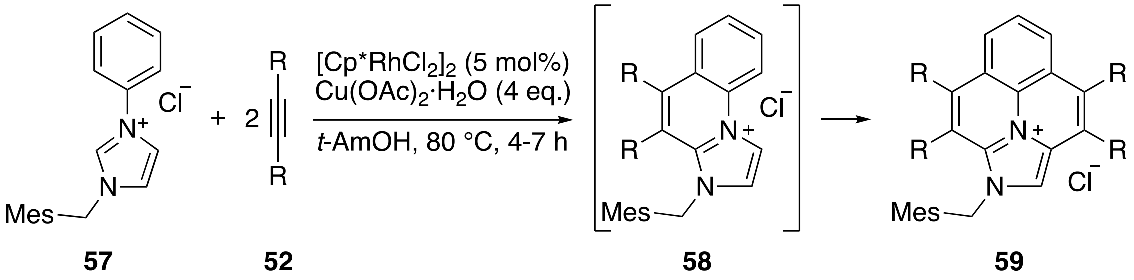
55 **52** **56**

Entry	**52**	R	**56**	Yield (%)[a]
1	**52a**	Ph	**56a**	99
2	**52b**	*p*-FC$_6$H$_4$	**56c**	90
3	**52c**	*p*-BrC$_6$H$_4$	**56f**	49
4	**52d**	*p*-MeC$_6$H$_4$	**56g**	73
5	**52e**	*p*-OMeC$_6$H$_4$	**56h**	80

[a] Isolated yields.

A synthesis of imidazolium salts **59** was developed by using two-fold C–H bond activation/annulation process. The C–H bond activation in phenylimidazolium salt **57** followed by annulation with alkynes **52** gave rise to intermediate imidazoquinolinium salts **58**, which then undergo the second C–H bond activation and annulation with alkynes **52** to form the final products **59** in up to 99% yield (Table 3).[57]

Table 3. Cascade C–H bond activation in the synthesis of imidazolium salts **59**.

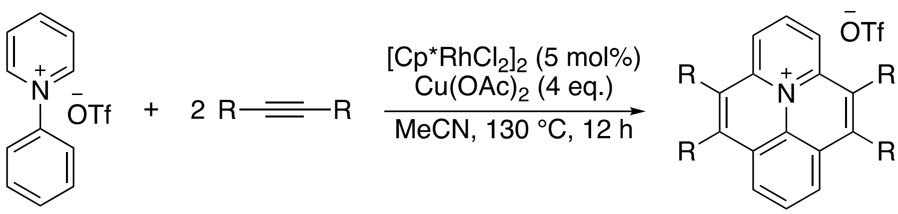


Entry	**52**	R	Reaction time	**59**	Yield (%)[a]
1	**52a**	Ph	4 h	**59a**	96
2	**52c**	*p*-FC_6H_4	6 h	**59b**	99
3	**52f**	*p*-BrC_6H_4	7 h	**59c**	92
4	**52g**	*p*-MeC_6H_4	4 h	**59d**	91
5	**52h**	*p*-$OMeC_6H_4$	4 h	**59e**	96

[a] Isolated yields.

A two-fold C–H bond activation was also used in syntheses of polycyclic quinolinium salts **61**. The substrate 1-phenylpyridinium (**60**) underwent cascade C–H bond activation with two equivalents of alkynes **52** yielding in the final products **61** with the yields up to 92% (Table 4).[58]

Table 4. Cascade C–H bond activation in the synthesis of polycyclic quinoliniums **61**.



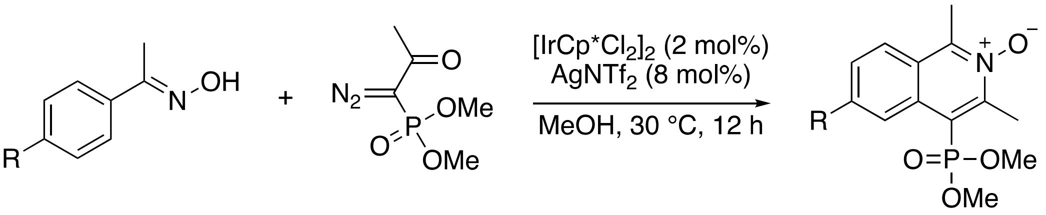
60 **52** **61**

Entry	**52**	R	**61**	Yield (%)[a]
1	**52a**	Ph	**61a**	92
2	**52c**	*p*-FC_6H_4	**61b**	92
3	**52d**	Et	**61c**	60
4	**52e**	2-thienyl	**61d**	52
5	**52f**	*p*-BrC_6H_4	**61e**	89

[a] Isolated yields.

A C–H activation annulation reaction sequence can be also used for synthesis of other *N*-heterocycles. Such an example is a synthesis of aromatic *N*-oxides. A series of isoquinoline *N*-oxides **64** was prepared by an iridium complex catalysed C–H bond activation in aryloximes **62** followed by annulation with Ohira-Bestman's diazophosphonate **63** (Table 5). The reactions proceeded to furnish products **64** in up to 96% yields.[53]

Table 5. C–H bond activation in aryloximes **62** catalysed by Ir^{III} complex.



62 **63** **64**

Entry	**62**	R	**64**	Yield (%)[a]
1	**62a**	Ph	**64a**	85
2	**62b**	Me	**64b**	96
3	**62c**	OH	**64c**	80
4	**62d**	F	**64d**	78
5	**62e**	Br	**64e**	83

[a] Isolated yields.

3.5. Synthesis of substituted phenanthridines

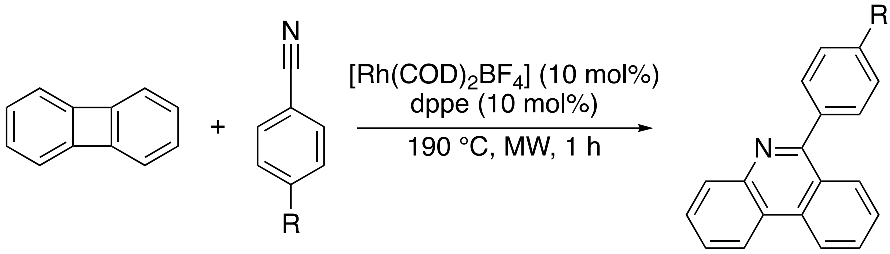
Phenanthridines are an important class of *N*-heterocyclic compounds. Application of such compounds is in medicinal[59] and material chemistry.[60] A substituted phenanthridine structural motif can be found in drugs, which possess a broad spectrum of biological activities such as antituberculosis,[61] antibacterial,[62] and antitumoral activity.[63] Finally, it is relevant to mention, that substituted phenanthridines can act as suitable substrates for C–H bond activation to synthesize structurally more complex compounds. Thanks to these applications, new methodologies are being developed in order to synthesize new types of substituted phenanthridines and compounds with the phenanthridine structural motif.[64]

3.5.1. C–C bond cleavage

Catalytic C–C bond cleavage followed by reactions with various substrates allows direct functionalization of unreactive C–C bond. The best substrates for C–C bond cleavage are carbocyclic compounds, such as those possessing strained cyclopropane and cyclobutene rings. The release of the ring strain of such compounds facilitates the C–C bond cleavage.[65]

Our group has developed a method for a single step synthesis of substituted phenanthridines **67**. Biphenylene (**65**) having the cyclobutadiene ring underwent C–C bond cleavage by a reaction with a Rh^I catalyst under microwave irradiation. It was followed by insertion of nitriles **66** giving rise to substituted phenanthridines **67** (Table 6).[66]

Table 6. Single step synthesis of substituted phenanthridines **67**.

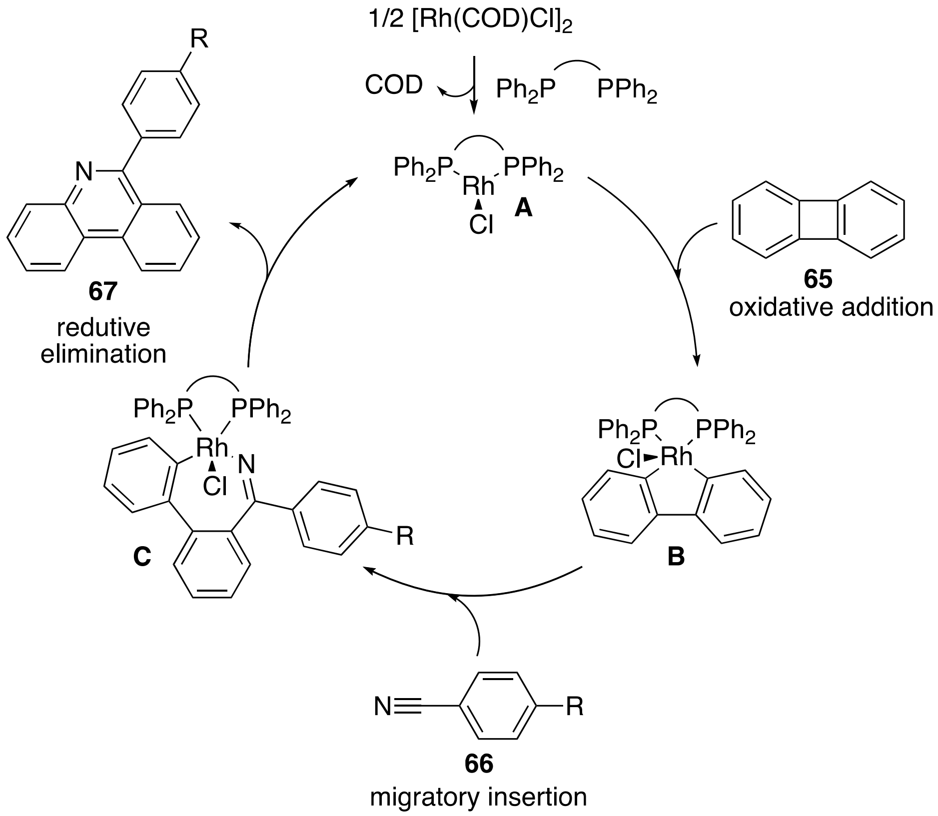


65 **66** **67**

Entry	**66**	R	**67**	Yield (%)[a]
1	**66a**	H	**67a**	92
2	**66b**	CF_3	**67b**	78
3	**66c**	Cl	**67c**	40
4	**66d**	OMe	**67d**	27
5	**66e**	Ph	**67e**	15

[a] Isolated yields.

The proposed catalytic cycle for C–C bond cleavage in biphenylene followed by a reaction with alkynes is depicted in Scheme 21. The first step of the catalytic cycle is ligand exchange in a Rh^I complex to form the catalytically active species **A**. Then oxidative addition of the **A** to the C–C bond of the cyclobutadiene ring in biphenylene (**65**) gives rise to the 5-membered rhodacycle **B**. Migratory insertion of nitrile **66** into **B** forms the 7-membered intermediate **C**. The last step, reductive elimination, releases product **67** and the catalytically active species **A** enters the catalytic cycle again.[67]

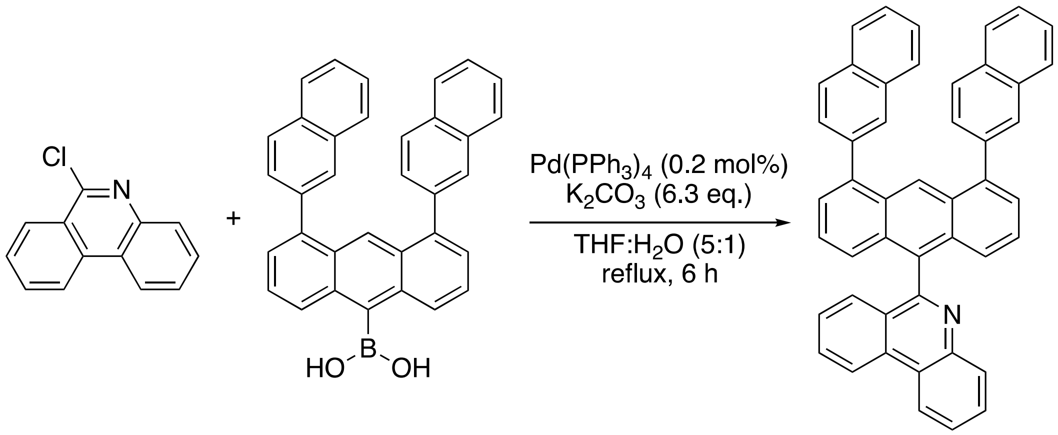


Scheme 21. Catalytic cycle of C–C bond cleavage in biphenylene (**65**) and reaction with a nitrile **66**.

3.5.2. Suzuki-Miyaura cross-coupling

Suzuki-Miyaura cross-coupling of electrophilic unsaturated carbon centres, such as in alkenyl, alkynyl, or aryl compounds, with boronic acids or their derivatives catalysed by palladium complexes, has become widely used reaction in organic synthesis.[68] The cross-coupling proceeds usually between an unsaturated halides and boronic acids (or their esters), and results ín the formation of a new C–C bond.[69] A suitable unsaturated halides for Suzuki-Miyaura cross-coupling approach to substituted phenanthridines is 6-chlorophenanthridine (**68**).

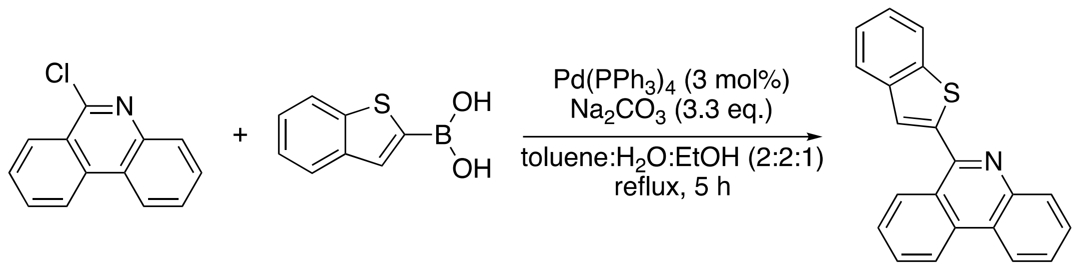
For example, 6-chlorophenanthridine (**68**) was used in a synthesis of anthracene derivative **70a** that was applied in organic electronic devices. By using this approach a series of compounds with the phenanthridine structural motif was synthesized in one step process (Scheme 22). As a typical example may serve a reaction of 6-chlorophenanthridine (**68**) with boronic acid **69a** that furnished product **70a** in 55% yield.[70]



68 **69a** **70a**, 55%

Scheme 22. Suzuki cross-coupling in the synthesis of the anthracene derivative **70a**.

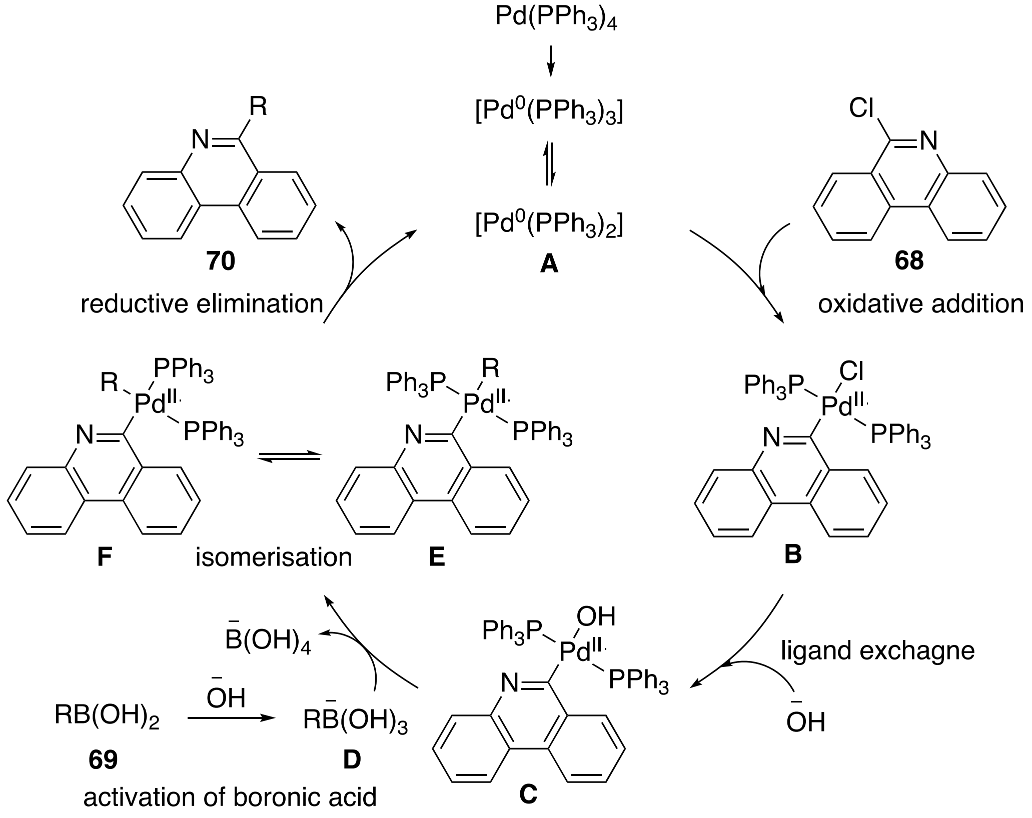
6-Chlorophenanthridine (**68**) was also used in for Suzuki-Miyaura cross-coupling with boronic acid **69b** resulting in the formation of phenanthridine **70b** with 79% yield (Scheme 23). This compound was an intermediate in the synthesis of highly fluorescent Ir^{III} complexes used in cell imaging.[71]



68 **69b** **70b**, 79%

Scheme 23. Synthesis of substituted phenanthridine **70b**.

Mechanism of Pd^0 catalysed Suzuki cross-coupling is depicted in Scheme 24. It begins with formation of the catalytically active species **A** by ligand dissociation from Pd(PPh$_3$)$_4$. Then, oxidative addition into the C–Cl bond in **68** takes place to form the intermediate **B**. Ligand exchange in the organopalladium complex **B** by hydroxide anion give rise to intermediate **C**, which then reacts with activated boronic acid **D** to form *trans* organopalladium complex **E**. The subsequent isomerization of the *trans*-intermediate **E** to the *cis*-intermediate **F** is necessary for reductive elimination step. By the reductive elimination, the product **70** is released and the catalytically active Pd^0 species **A** is renewed.[72,73]

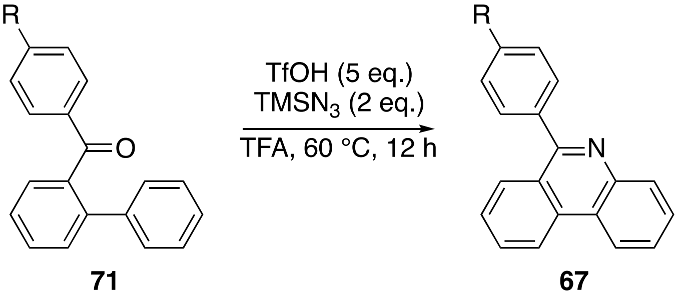


Scheme 24. Mechanism of Pd^0 catalysed Suzuki cross-coupling.

3.5.3. Other methods for the synthesis of substituted phenanthridines

One of the approaches towards substituted phenanthridines **67** is an metal-free intramolecular nitrogenation of ketones **71** with trimethylsilyl azide. The reaction proceeded with variously substituted substrates giving the respective 6-substituted phenanthridines **67** in up to 95% yields (Table 7).[74]

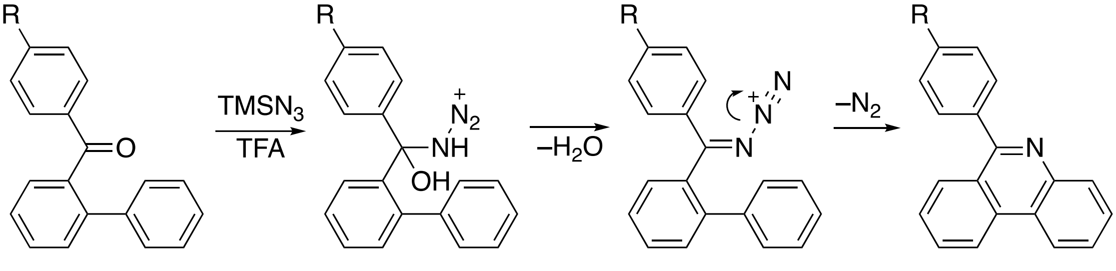
Table 7. Intramolecular nitrogenation in the synthesis of substituted phenanthridines **67**.



Entry	**71**	R	**67**	Yield (%)[a]
1	**71a**	CF_3	**67b**	86
2	**71b**	Cl	**67c**	89
3	**71c**	F	**67f**	95
4	**71d**	Me	**67g**	56
5	**71e**	NO_2	**67h**	94

[a] Isolated yields.

Mechanism of the above-mentioned transformation is depicted in Scheme 25. Firstly, hydrazoic acid is generated from $TMSN_3$ in strongly acidic trifluoroacetic acid, which attacks **71** to afford intermediate **A**. During the dehydration step, product **B** is formed, which undergoes a Friedel-Crafts reaction accompanied by loss of N_2, forming final product **67**.

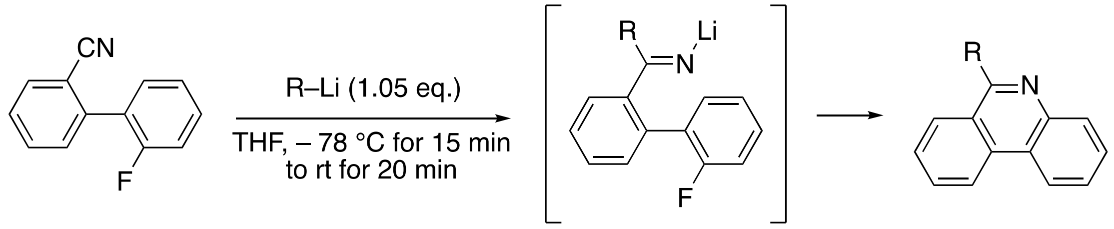


71 **A** **B** **67**

Scheme 25. Mechanism of intramolecular nitrogenation of ketones **71**.

Another approach to substituted phenanthridines is based on 1,2-addition of organolithium reagents to the nitrile group of 2-(2-fluorophenyl)benzonitrile (**72**), forming intermediate **73**. Following intramolecular nucleophilic substitution gives rise to 6-substituted phenanthridines **70** with yields up to 94% (Table 8).[75]

Table 8. Synthesis of substituted phenanthridines **70** by organolithium reagents.



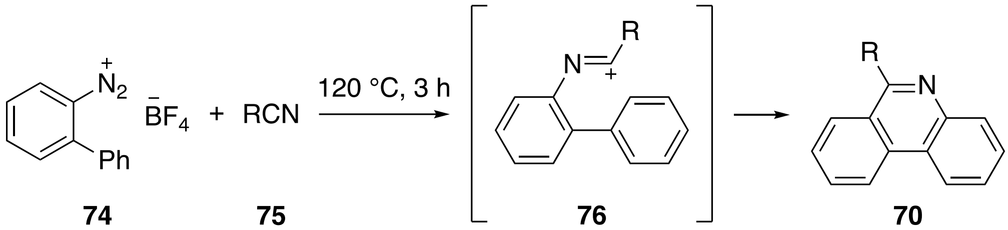
72 **73** **70**

Entry	R	70	Yield (%)[a]
1	Me	**70c**	87
2	*n*-Bu	**70d**	87
3	*t*-Bu	**70e**	85
4	*N*,*N*-diethyl	**70f**	88
5	piperidin-1-yl	**70g**	94

[a] Isolated yields.

Using methods of classical organic chemistry, the coupling reaction of aryldiazonium salt **74** with nitriles **75** was developed to prepare 6-substituted phenanthridines **70**. First step is formation of carbocation **76** followed by intramolecular electrophilic aromatic substitution to form the final products **70**. Furthermore, the reaction does not need any other additive and the products **70** were isolated in yields up to 88% (Table 9).[76]

Table 9. Synthesis of phenanthridines using aryldiazonium salt **74**.

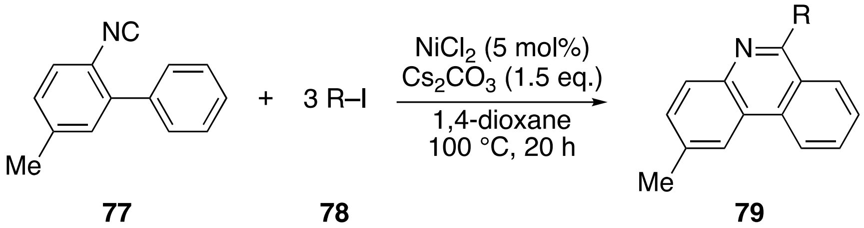


Entry	**75**	R	**70**	Yield (%)[a]
1	**75a**	Me	**70c**	88
2	**75b**	*n*-Pr	**70h**	86
3	**75c**	*i*-Pr	**70i**	76
4	**75d**	benzyl	**70j**	73
5	**75e**	3-thienyl	**70k**	78

[a] Isolated yields.

Among other methods allowing preparation of phenanthridines is a Ni-catalyzed radical perfluoroalkylation of aromatic isonitriles. Reactions of isonitrile **77** with perfluoroalkyl iodides **78** furnished 6-substituted phenanthridines **79** in yields up to 64% (Table 10).[77]

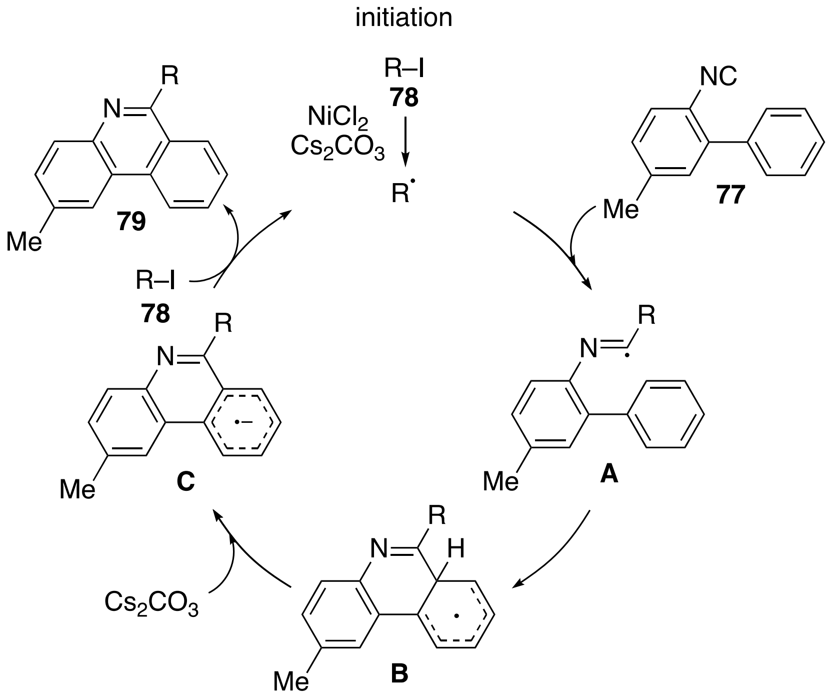
Table 10. Radical Ni^{II} catalysed synthesis of substituted phenanthridines **79**.



Entry	**78**	R	**79**	Yield (%)[a]
1	**78a**	CF_3	**79a**	60
2	**78b**	C_6F_{13}	**79b**	64
3	**78c**	C_8F_{17}	**79c**	55
4	**78d**	$C_{10}F_{21}$	**79d**	48
5	**78e**	$C_{12}F_{25}$	**79e**	50

[a]Isolated yields.

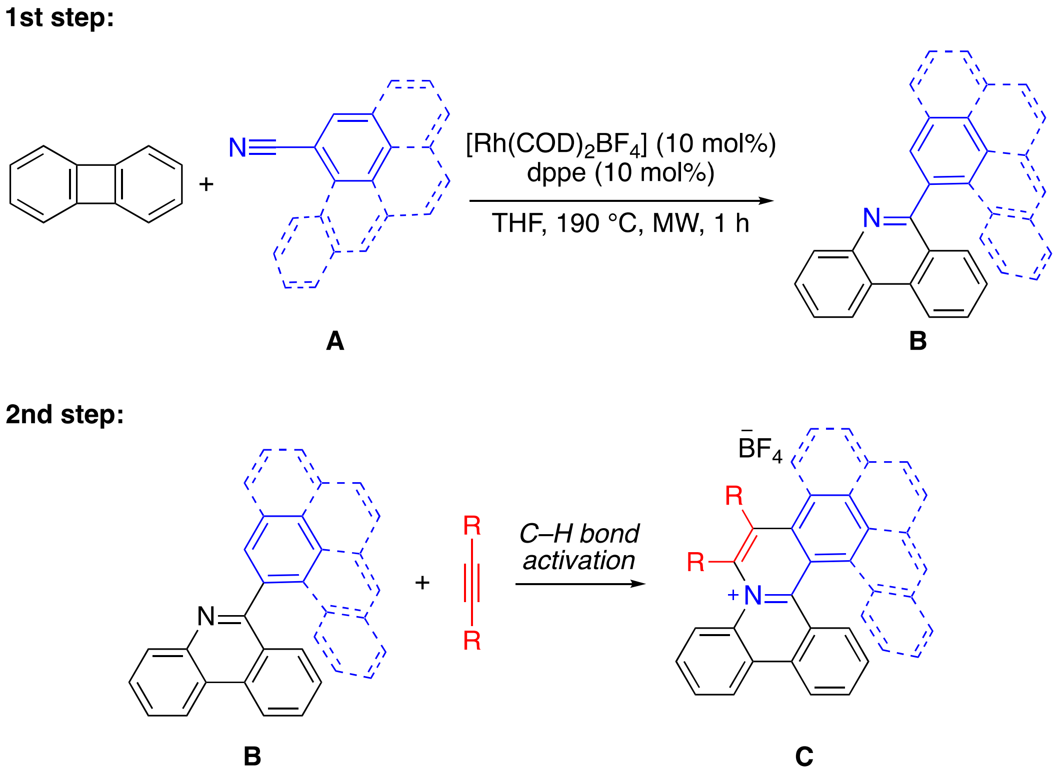
The catalytic cycle of the Ni-catalysed perfluoroalkylation is depicted in Scheme 26. The first step, initiation, generates a perfluoroalkyl radical. The initiation is catalysed by $NiCl_2$ and Cs_2CO_3, although the mechanism of initiation is not yet well understood. The second step is addition of the perfluoroalkyl radical to isonitrile **77** giving rise to the imidoyl radical **A**. The following cyclization forms the cyclohexadienyl radical **B**, which undergoes deprotonation by Cs_2CO_3 to give the radical anion **C**. Further reaction of **C** with perfluoroalkyl iodide is a single electron transfer process, which allows the formation of the final product **79** and the perfluoroalkyl radical to sustain the radical chain reaction.



Scheme 26. Catalytic cycle of radical Ni^{II} catalysed perfluoroalkylation of isonitrile.

4. Results and discussion

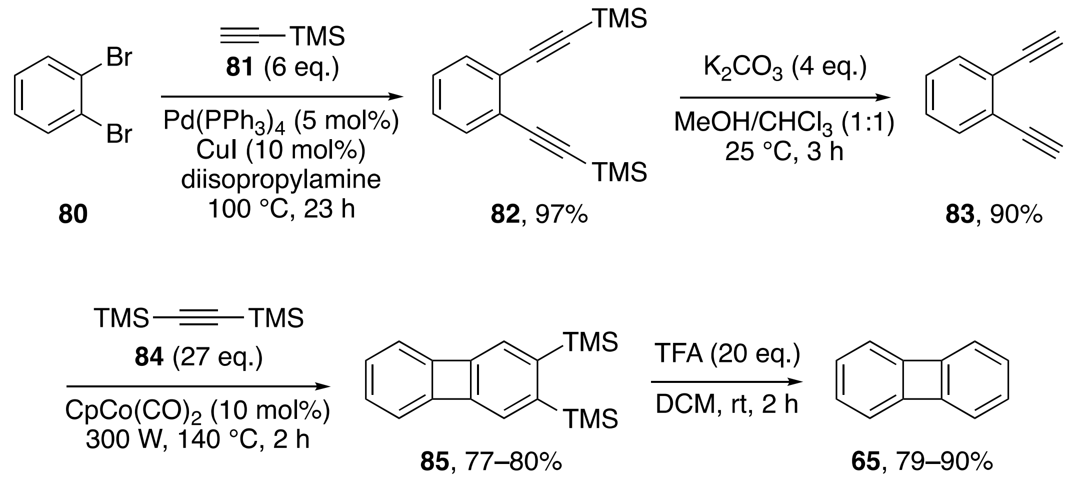
A synthetic pathway towards helical *N*-heterocycles **C** was envisioned to be carried out in two steps. The first step comprises a catalytic C–C bond cleavage in biphenylene followed by insertion of nitriles **A**, under conditions developed in our group,[66] giving rise to substituted phenanthridines **B**. The second step consists of catalytic C–H bond activation in the prepared phenanthridines **B** followed by annulation with alkynes to form the desired cationic *N*-heterocycles **C** with the helical structural motif (Scheme 27).



Scheme 27. A proposed synthetic route to helical cationic *N*-heterocycles.

4.1. Synthesis of biphenylene

Biphenylene **65** was synthesized according to the published procedure in four steps (Scheme 28).[78] Firstly, Sonogashira coupling of 1,2-dibromobenzene (**80**) with trimethylsilylacetylene (**81**) was performed. The reaction proceeded in almost quantitative yield and the trimethylsilylated diyne **82** was isolated in 97% yield. The second step comprised a simple deprotection of **82** by using K_2CO_3, and diyne **83** was isolated in 90% yield. The compound **83** then underwent [2+2+2] cyclotrimerization with bis(trimethylsilyl)acetylene (**84**) catalyzed by Volhardt's catalyst ($CpCo(CO)_2$). The product **85** was isolated in the range of 77–80% yields. The next step consisted of desilylation under acidic conditions (CF_3COOH). Biphenylene (**65**) was isolated in the range of 79–90% yields. Since the synthesis of biphenylene **65** is well established in our group, the structure of intermediates **82**, **83** and **85** was confirmed only by ^{1}H NMR analysis. The structure of the final product of the synthetic route, biphenylene (**65**), was confirmed by ^{1}H NMR and ^{13}C NMR analysis.



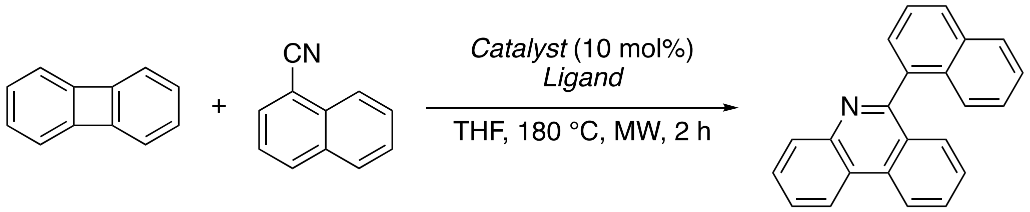
Scheme 28. Synthesis of biphenylene (**65**).

4.2. Formation of phenanthridines by C–C bond cleavage

4.2.1. Insertion of 1-cyanonaphthalene

Initially, I tried to carry out insertion of 1-cyanonaphthalene (**75f**) into the central C–C bond of biphenylene (**65**) (Table 11). A mixture of biphenylene **65** and **75f** was subjected to catalytic conditions (([Rh(COD)$_2$BF$_4$]/dppe) successfully developed for insertion of benzonitriles in our group (entry 1).[66] Unfortunately, the desired product **70l** was formed only in 3% yield. In order to improve the yield of the reaction, catalytic systems using other ligands were tested as well. When dppp was used (entry 2), formation of product **70l** was not observed (according to TLC analysis of the reaction mixture). The use of dppb (entry 3) and PPh$_3$ (entry 4) did not improve the reaction outcome, and the desired product **70l** was formed in 2% yields only. The change of a Rh^I catalyst for an Ir^I catalyst did not improve the yield of the reaction either, product **70l** was formed in only 1% yield (entry 5). According to the respective TLC analyses, the starting material remained unreacted and formation of side-products was not detected. Nitrile **75f** seems to be an unsuitable reaction partner in the insertion reaction.

Table 11. Screening of the C–C bond cleavage reaction conditions.



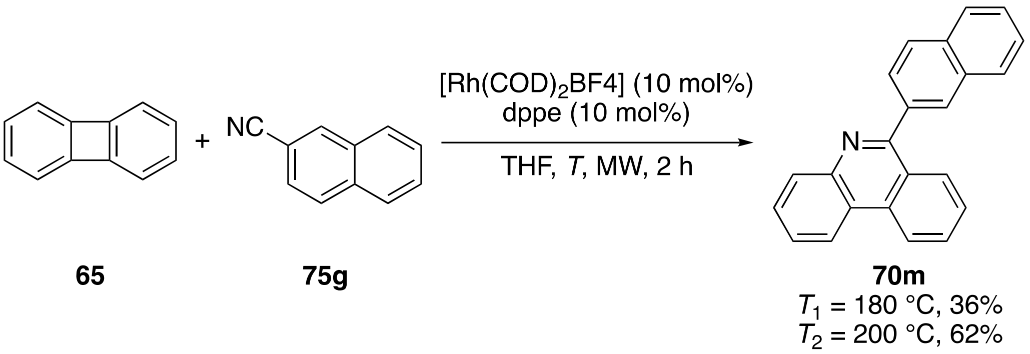
65 **75f** **70l**

Entry	Catalyst	Ligand (mol%)	Yield (%)[a]
1	[Rh(COD)$_2$BF$_4$]	dppe (10)	3
2	[Rh(COD)$_2$BF$_4$]	dppp (10)	0
3	[Rh(COD)$_2$BF$_4$]	dppb (10)	2
4	[Rh(COD)$_2$BF$_4$]	PPh$_3$ (20)	2
5	[Ir(COD)Cl]$_2$	dppe (10)	1

[a]Isolated yields.

4.2.2. Insertion of 2-cyanonaphthalene

Since the insertion of 1-cyanonaphthalene (**75f**) into the C–C bond in biphenylene (**65**) did not proceed as expected, I decided to try a reaction with 2-cyanonaphthalene (**75g**) that has a less sterically hindered nitrile group. Running the reaction under the previously developed reaction conditions using (([Rh(COD)$_2$BF$_4$]/dppe) as a catalyst (Scheme 29, T_1), the desired product **70m** was isolated in 36% yield. Carrying out the reaction at even higher temperature of 200 °C allowed to obtain product **70m** in 62% isolated yield (Scheme 29, T_2). The structure of phenanthridine **70m** was confirmed by single crystal X-ray diffraction analysis (Figure 4).



Scheme 29. Formation of phenanthridine **70m** by a reaction of biphenylene (**65**) with 2-cyanonaphthalene (**75g**).

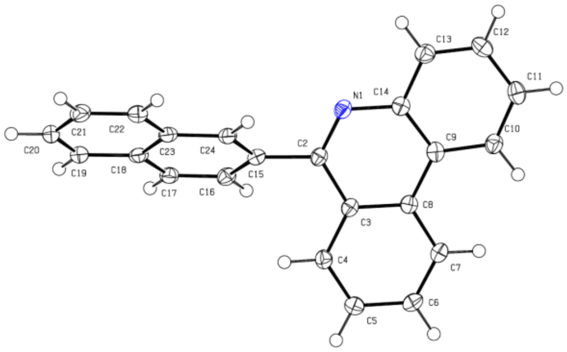
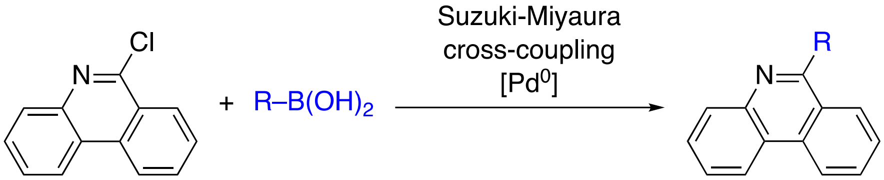


Figure 4. ORTEP drawing of **70m**.

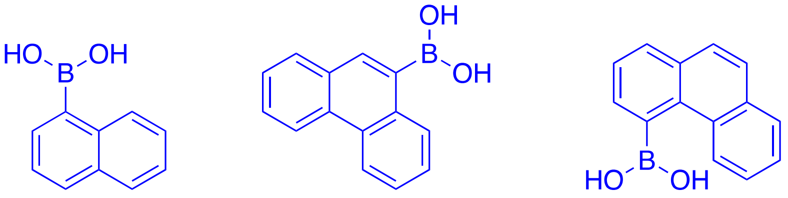
4.3. Formation of phenanthridines by Suzuki-Miyaura cross-coupling

A preparation of 6-(naphthalen-1-yl)phenanthridine (**70l**) was not successful using catalytic C–C bond cleavage; therefore, I came up with a new approach to synthesize 6-substituted phenanthridines by using Pd^0 catalysed Suzuki-Miyaura cross-coupling (Scheme 30). As the coupling partners were chosen 6-chlorophenanthridine (**68**) and boronic acids **69** (Figure 5).



68 **69** **70**

Scheme 30. Suzuki-Miyaura cross-coupling reaction of phenanthridine **68** with boronic acids **69** for syntheses of substituted phenanthridines **70**.



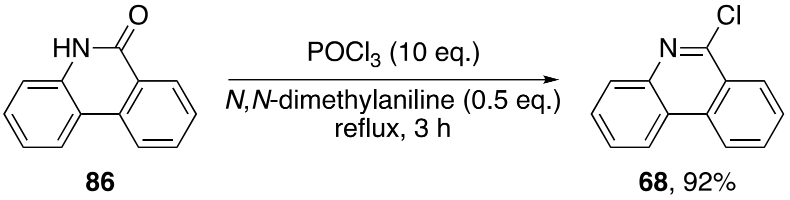
69c **69d** **69e**

Figure 5. Boronic acids **69** for Suzuki-Miyaura cross-coupling reaction.

Boronic acids **69c** and **69d** depicted in Figure 5 are commercially available and cheap substrates. Phenanthren-4-ylboronic acid **69e** is not commercially available and therefore a synthesis of **69e** had to be developed.

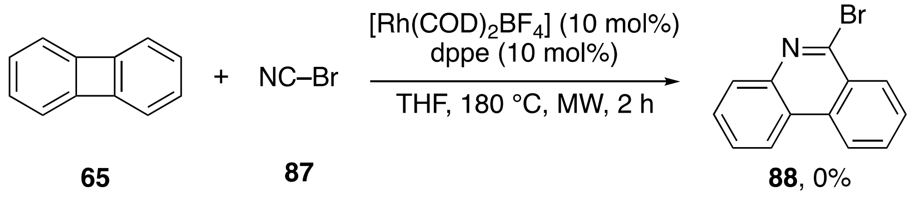
4.3.1. Synthesis of 6-halophenanthridines

Synthesis of 6-chlorophenanthridine (68). 6-Chlorophenanthridine (**68**) is commercially available, but it is not a cheap substance. Therefore, I decided to synthesize **68** from a very cheap substrate, phenanthridin-6(5*H*)-one (**86**), by dehydration-monochlorination with $POCl_3$ (Scheme 31). The reaction was carried out under previously reported conditions.[79] The reaction was carried out on 15 mmol scale with respect to **86** and 6-chlorophenantridine (**68**) was isolated in 92% yield.



Scheme 31. Synthesis of 6-chlorophenanthridine (**68**).

Synthesis of 6-bromophenanthridine (88). I also tried to synthesize 6-bromophenanthridine (**88**) as the starting material for the coupling reactions, as it possesses a more reactive C–Br bond. An attempt to apply catalytic C–C bond activation in biphenylene (**65**) and insertion of cyanogen bromide (**87**) did not lead to the desired product **88** (Scheme 32). After 2 hours, pieces of a black solid substance were found in the reaction mixture, which were soluble in water. However, according to a TLC analysis the starting material remained unreacted and no product of the reaction was detected. Biphenylene (**65**) was recovered in the quantitative amount.



Scheme 32. Attempt to synthesize 6-bromophenanthridine (**88**) using C–C bond cleavage.

4.3.2. Synthesis of phenanthren-4-ylboronic acid

For the synthesis of phenanthren-4-ylboronic acid (**69e**) I chose as a starting material 4-bromophenanthrene (**90**), which can be converted in one step through bromine/lithium exchange followed by electrophilic quench to the desired boronic acid **69e** (Figure 6). 4-Bromophenanthrene (**90**) was synthesized in 3 steps following published procedure.[80]

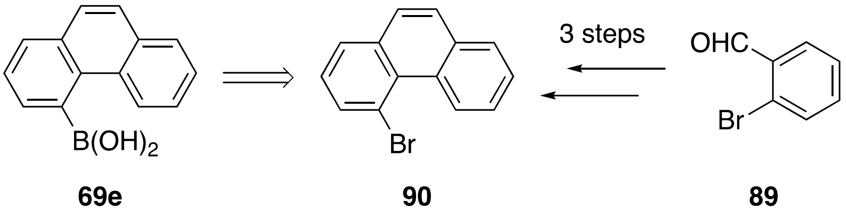
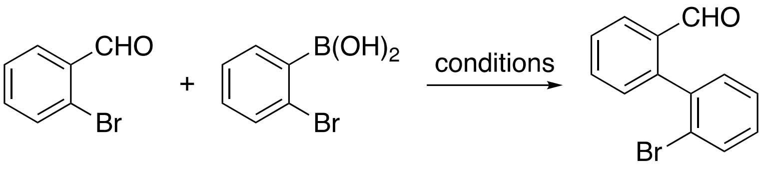


Figure 6. Designed synthetic route towards phenanthrene-4-ylboronic acid (**69e**).

In the first step was carried out Suzuki-Miyaura cross-coupling of 2-bromobenzaldehyde (**89**) with 2-bromophenylboronic acid (**69f**) to form 2'-bromo-[1,1'-biphenyl]-2-carbaldehyde (**91**). Initially, the reaction was carried out using published conditions: $Pd(PPh_3)_4$ (10 mol%), Et_3N (3 eq.) in DMF at 90 °C for 2 h under argon atmosphere (Table 12, Entry 1). The reaction was monitored using TLC analysis and after 2 hours, the starting material was still present in the reaction mixture. Therefore, the reaction was continued for additional 6 hours. According to subsequent TLC analyses, the starting material, 2-bromobenzaldehyde (**89**), was still present in the reaction mixture. Despite of that I decided to stop the reaction. After workup of the reaction mixture, only traces of the product **91** were detected by using TLC analyses. Separation of the reaction mixture components by column chromatography did not lead to isolation of any product. The starting material, 2-bromobenzaldehyde (**89**), was almost fully recovered. Second attempt to synthesize product **91** was also not successful (Entry 2). The same reaction conditions (Entry 1) were used, but the reaction time was prolonged to 12 h. The outcome of the reaction was the same. Only traces of the product **91** were observed by respective TLC analyses. In the next attempt (Entry 3), the reaction was done using other published conditions: $Pd(OAc)_2$ (10 mol%), PPh_3 (25 mol%), NaOAc (1.5 eq.) in DMF at 80 °C for 3 h.[81] The reaction time was again prolonged to 6 h, because, according to TLC analyses, the starting material was not fully reacted. Although starting material was still present in reaction mixture, I decided to stop the reaction. Unfortunately, these new conditions led to the same result. Only traces of the product **91** were observed by TLC analyses and the starting material, 2-bromobenzladehyde (**89**), was recovered in almost quantitative amount. Then, I decided to try classical conditions for Suzuki-Miyaura cross-coupling, which were published for a similar reaction: $Pd(PPh_3)_4$ (2.5 mol%), K_2CO_3 (5 eq.) in THF/H_2O (5/1) at 90 °C for 24 h under argon atmosphere (Entry 4).[82] After 24 hours, the starting material was fully consumed and the product **91** was furnished in 75% isolated yield.

Table 12. Suzuki-Miyaura cross-coupling of 2-bromobenzaldehyde (**89**) with 2-bromophenylboronic acid (**69f**) under various conditions.



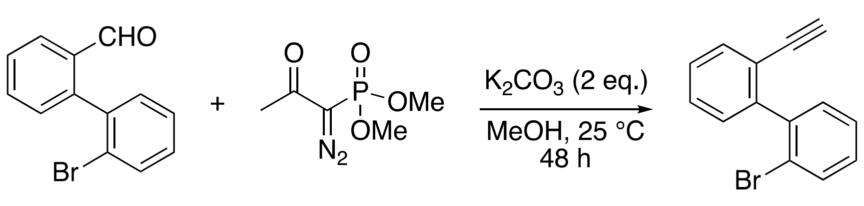
89 **69f** **91**

Entry	Catalyst (mol%)	Base (eq.)	Solvent	T (°C)	t (h)	Yield (%)[a]
1	$Pd(PPh_3)_4$ (10)	Et_3N (3)	DMF	90	8	0[b]
2	$Pd(PPh_3)_4$ (10)	Et_3N (3)	DMF	90	12	0[b]
3	$Pd(OAc)_2$ (10)	NaOAc (1.5)	DMF	80	6	0[b]
4	$Pd(PPh_3)_4$ (2.5)	K_2CO_3 (5 eq.)	THF/H_2O (5/1)	90	24	75

[a] Isolated yields.

[b] Traces of the product.

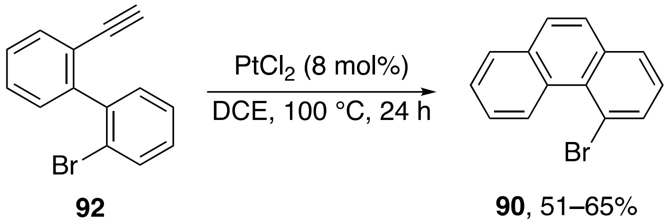
With 2'-bromo-[1,1'-biphenyl]-2-carbaldehyde (**91**) in hand, I proceeded to the next step, which was Seyferth-Gilbert homologation by Ohira-Bestmann reagent **63** (5 eq.) and K_2CO_3 (2 eq.) in MeOH at 25 °C during 48 h. The product of the reaction, 2-bromo-2'-ethynyl-1,1'-biphenyl (**92**), was furnished in the range of 48–73% isolated yields (Scheme 33).



91 **63** **92**, 48–73%

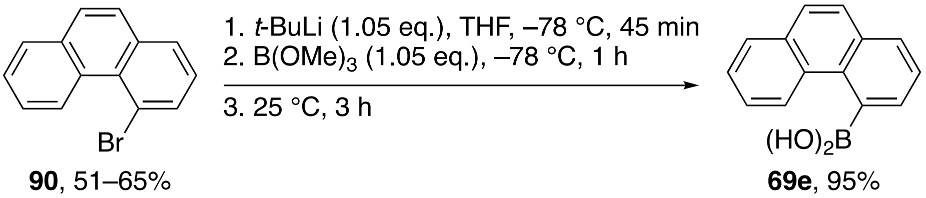
Scheme 33. Seyferth-Gilbert homologation of **91**.

The next step was cyclization of 2-bromo-2'-ethynyl-1,1'-biphenyl (**92**) by $PtCl_2$ (8 mol%) in DCE at 100 °C for 24 h. The product, 4-bromophenanthrene (**90**), was isolated in the range of 51–65% yields (Scheme 34).



Scheme 34. Cyclization of **92** by $PtCl_2$.

The final step, a preparation of phenanthren-4-ylboronic acid (**69e**), consisted of two steps and published conditions were used.[83] The first step was lithiation of 4-bromophenanthrene (**90**) by *t*-BuLi (1.05 eq.) in THF at –78 °C and the second step was electrophilic reaction with $B(OMe)_3$ (1.05 eq.) at –78 °C. Phenanthren-4-ylboronic acid (**69e**) was obtained in 95% isolated yield (Scheme 35). The boronic acid **69e** was not isolated completely pure according to NMR analyses, therefore it was crystalized to undergo single crystal X-ray diffraction analysis. Unfortunately, the results could not obtained before a deadline for submission of the diploma thesis.



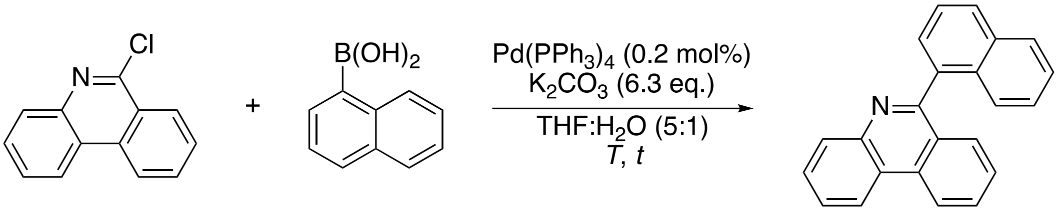
Scheme 35. Preparation of phenanthren-4-ylboronic acid (**69e**).

4.3.3. Coupling of 68 with naphthalen-1-ylboronic acid

The Suzuki-Miyaura cross-coupling of 6-chlorophenanthridine (**68**) with various boronic acids **69** was carried out previously by using the following conditions: $Pd(PPh_3)_4$ (0.2 mol%) as a catalyst and K_2CO_3 (6.3 eq.) as a base in a mixture of THF:H_2O (5:1) under reflux.[70] Therefore, I decided to apply these conditions for the coupling of 6-chlorophenanthridine (**68**) with naphthalen-1-ylboronic acid (**69c**) in order to prepare phenanthridine **70l**.

Firstly, I tried to perform the reaction in a sealed vial. This reaction was done without the use of a condenser and therefore the setup was very easy. Carrying out the reaction at 80 °C for 24 h furnished the product **70l** in 23% isolated yield in (Entry 1, Table 13). TLC analyses of the reaction mixture confirmed that the starting material did not fully react, and the unreacted 6-chlorophenanthridine (**68**) was successfully recovered. A reaction was also performed under reflux and the reaction mixture was monitored using TLC analyses (Entry 2). The starting material was not detected after 6 hours and the formation of only one product was observed. 6-(Naphth-1-yl)phenanthridine (**70l**) was isolated in 85% yield. Scale up of the reaction to 2 mmol (Entry 3) led to a lower yield of **70l**, which was isolated in 50% yield. Again, a TLC analysis of the reaction mixture showed the presence of **70l** and the unreacted starting material only.

Table 13. Screening of the Suzuki-Miyaura cross-coupling reaction conditions.



68 **69c** **70l**

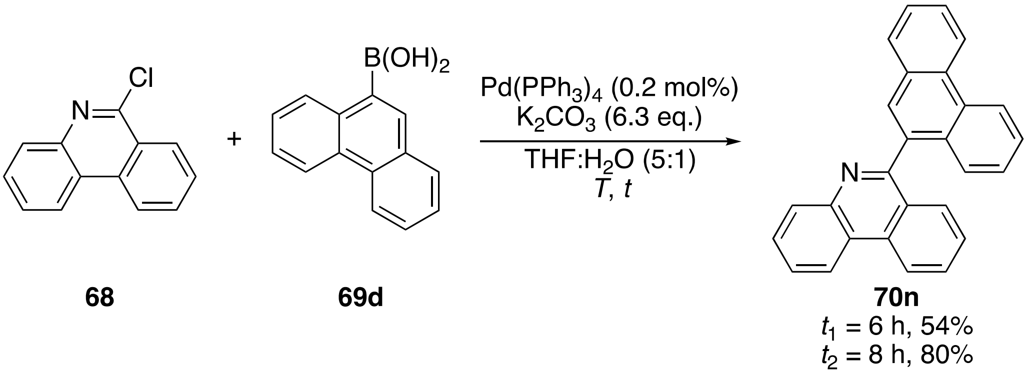
Entry	Scale (mmol)	Temperature *T*	Reaction time *t*	Yield (%)[a]
1[b]	0.6	80 °C	24 h	23
2	0.6	reflux	6 h	85
3	2	reflux	6 h	50

[a]Isolated yields.

[b]Reaction performed in sealed vial.

4.3.4. Coupling of 68 with phenanthren-9-ylboronic acid

The Suzuki-Miyaura cross-coupling reaction of 6-chlorophenanthridine (**68**) with phenanthren-9-ylboronic acid (**69d**) under published reaction conditions (6 h)[70] gave the product **70n** in 54% isolated yield (Scheme 36, t_1). The reaction was carried out once more using the same reaction conditions and its course was monitored by TLC analyses. After 8 hours, the starting material was fully consumed and only the formation of phenanthridine **70n** was observed. It was isolated in 80% yield (Scheme 36, t_2). Although the full conversion of the starting material was observed, a lower isolated yield can be rationalised by a very low solubility of phenanthridine **70n** in common organic solvents, such as methanol, ethanol, ethylacetate, dichloromethane, chloroform, diethylether, and hexane. Thanks to its low solubility, phenanthridine **70n** crystalized very easily and its structure was confirmed by single crystal X-ray diffraction analysis (Figure 7).



Scheme 36. Synthesis of 6-(phenanthrene-9-yl)phenanthridine (**70n**) by Suzuki-Miyaura cross-coupling.

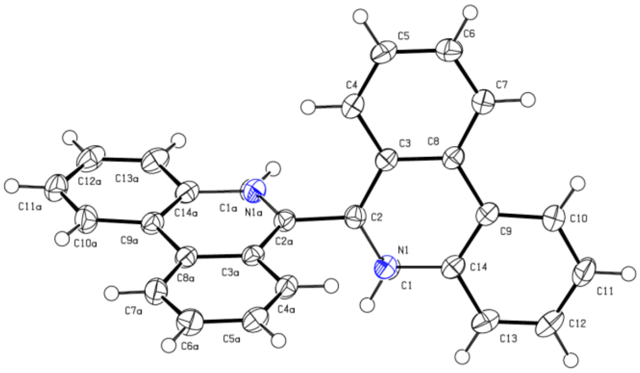
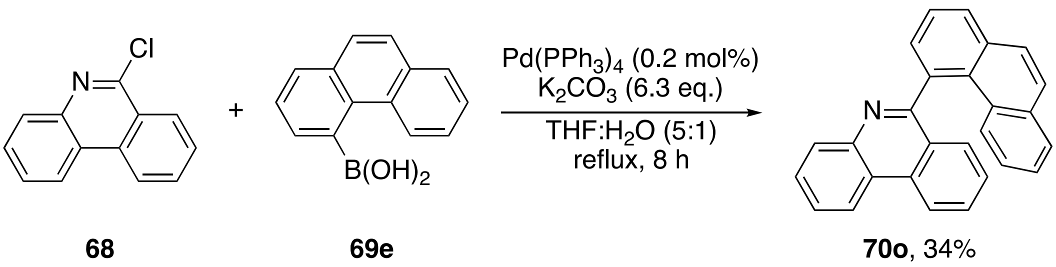


Figure 7. ORTEP drawing of **70n**. Ellipsoids are drawn with 50% probability.

4.3.5. Coupling of 68 with phenanthren-4-ylboronic acid

The Suzuki-Miyaura cross-coupling of 6-chlorophenanthridine (**68**) with phenanthren-4-ylboronic acid (**69e**) under previously optimized reaction conditions ($Pd(PPh_3)_4$ (0.2 mol%), K_2CO_3 (6.3 eq.) in THF:H_2O (5:1) under reflux for 8 h) was done. The reaction mixture was monitored by TLC analyses and the reaction was stopped after 8 h, when the boronic acid **69e** was fully consumed. The reaction gave the product, 6-(phenanthren-4-yl)phenanthridine (**70o**), in 34% isolated yield (Scheme 37). Thanks to the respective TLC analyses of the reaction mixture, formation of two more products was observed. These compounds unfortunately could not be separated from the starting material, 6-chlorophenanthridine (**68**).



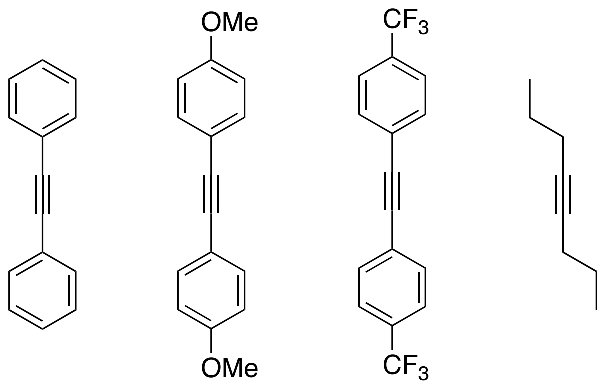
Scheme 37. Formation of 6-(phenanthrene-4-yl)phenanthridine (**70o**).

4.4. Activation of C–H bond in phenanthridines

During the work on my bachelor thesis, I found out that the best catalytic conditions for C–H bond activation in phenanthridines, and the subsequent annulation with alkynes, were as follows: [Cp*$RhCl_2$]$_2$ (10 mol%), $AgBF_4$ (1 eq.) and $Cu(OAc)_2$ (1 eq.) in DCE under 100 °C during 24 hours.[84] Therefore these conditions were proposed for C–H activation /annulation sequence in 6-substituted phenanthridines **70l**, **70m**, **70n** and **70o**.

4.4.1. Synthesis of substituted diarylalkynes

For the annulation step of the C–H bond activation in phenanthridines **70** were chosen four different alkynes **52** (Figure 8).

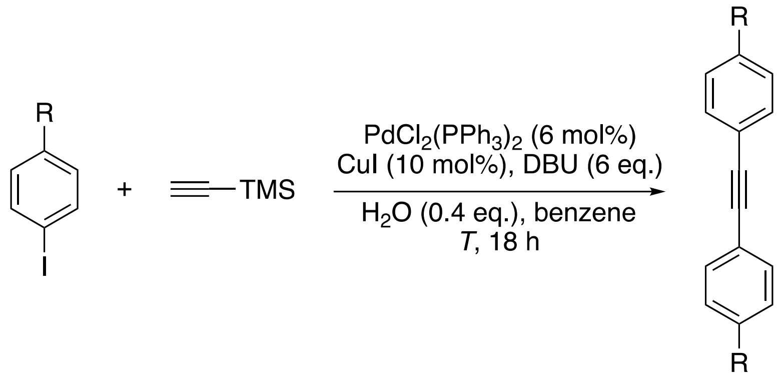


52a **52h** **52i** **52j**

Figure 8. Alkynes **52** proposed for the annulation step of C–H bond activation.

Alkynes **52a** and **52j** are commercially available substrates. Alkynes **52h** and **52i** were prepared by a modified single step Sonogashira coupling reaction,[85] catalysed by $PdCl_2(PPh_3)_2$ in the presence of CuI and DBU (Table 14). A reaction of 4-iodoanisole (**93a**) with trimethylsilylacetylene (**81**) at 60 °C for 18 h giving rise to 1,2-bis(4-methoxyphenyl)ethyne (**52h**) in 63% yield. A reaction of 4-iodobenzotrifluoride (**93b**) with trimethylsilylacetylene (**81**) at 20 °C for 18 h furnished 1,2-bis(4-(trifluoromethyl)phenyl)ethyne (**52i**) in 90% yield.

Table 14. Modified Sonogashira coupling in the synthesis of alkynes **52**.



93 **81** **52**

Entry	**93**	R	Temperature *T*	**52**	Yield (%)[a]
1	**93a**	OMe	60 °C	**52h**	63
2	**93b**	CF_3	25 °C	**52l**	90

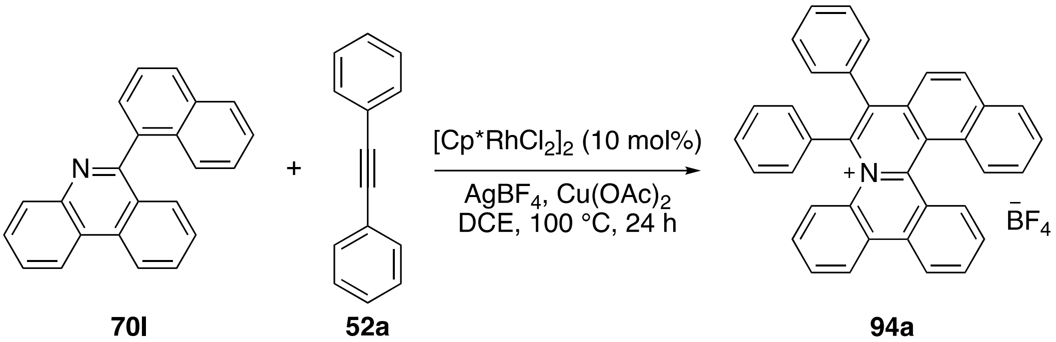
[a] Isolated yields.

4.4.2. Synthesis of benzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium salts

With **70l** in hand I decided to explore its reactivity in C–H activation/annulation reaction with various alkynes. Firstly, I tried C–H bond activation in phenanthridine **70l** and annulation with diphenylethyne (**52a**) (Table 15). The previously found reaction conditions for the C–H bond activation/annulation sequence for phenanthridines ($[Cp^*RhCl_2]_2$ (10 mol%), $AgBF_4$ (1 eq.) and $Cu(OAc)_2$ (1 eq.) in DCE under 100 °C during 24 hours) seemed to be satisfactory and the respective product **94a (**6,7-diphenylbenzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate) was isolated in a rather mediocre 27% yield (Entry 1). In order to assess an effect of amounts of additives on the product yield, the reaction was run using following conditions: $[Cp^*RhCl_2]_2$ (10 mol%), $AgBF_4$ (1.35 eq.), $Cu(OAc)_2$ (2 eq.) and 2 equivalents of alkyne **52a**. The product **94a** was isolated in 30% yield (Entry 2). Since the increase of the yield was marginal, the amount of $AgBF_4$ was lowered to 1 equivalent as well as that of alkyne **52a** (1 eq.), and the load of $Cu(OAc)_2$ remained unchanged. **94a** was isolated in 22% isolated yield (Entry 3). Next, the amount of $Cu(OAc)_2$ was also lowered to 1.1 equivalent (Entry 4), and the product **94a** was furnished in 29% isolated yield. Further reduction of the $Cu(OAc)_2$ amount to 0.2 equivalent lead to decrease of the **94a** yield to mere 8% (Entry 5).

Characterization of the product **94a** was challenging, as signals in ^1H NMR spectra at 7.09 ppm, 7.23 ppm and 7.60 ppm are broad singlets (Figure 9). Further ^1H NMR experiments were done under temperatures of 5 °C, 40 °C and 50 °C in order to affect the rotation of the phenyl rings. Unfortunately, no resolution of broad singlets was observed. Therefore, the structure of the product **94a** was unequivocally confirmed by single crystal X-ray diffraction analysis (Figure 10).

Table 15. Screening additives amounts in the C–H bond activation/annulation of **70l** with diphenylethyne (**52a**).



Entry	**52a** (eq.)	$AgBF_4$ (eq.)	$Cu(OAc)_2$ (eq.)	Yield (%)[a]
1	1	1	1	27
2	2	1.35	2	30
3	1	1	2	22
4	1	1	1.1	29
5	1	1	0.2	8

[a]Isolated yields.

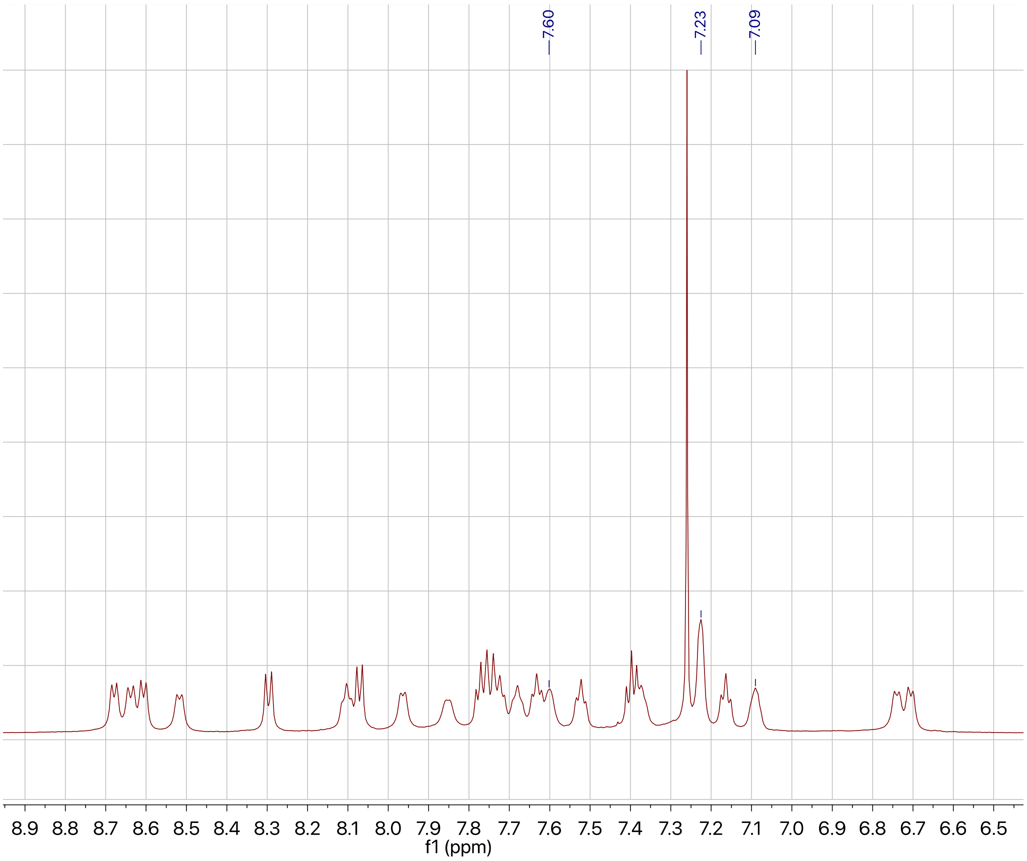


Figure 9. Region of ^1H NMR spectrum of **94a**.

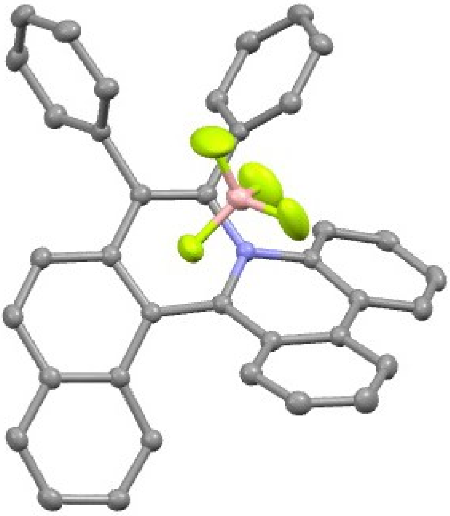
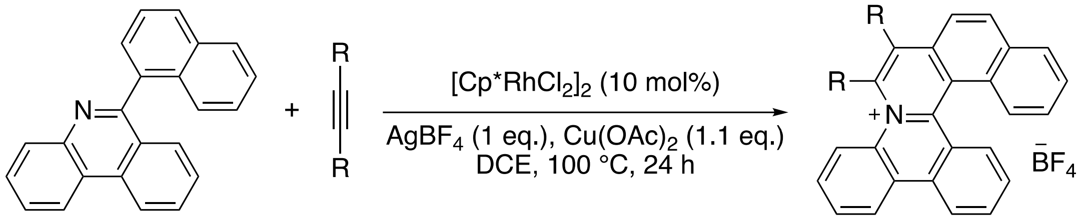


Figure 10. ORTEP drawing of **94a**.

On the basis of abovementioned results, the following conditions were used for subsequent catalytic C–H bond activation/annulation process of phenanthridine **70l** with alkynes **52**: $[Cp^*RhCl_2]_2$ (10 mol%) as a catalyst, and $AgBF_4$ (1 eq.), $Cu(OAc)_2$ (1.1 eq.) as additives in DCE at 100 °C for 24 hours (Table 16).

A reaction of 6-(naphthalen-1-yl)phenanthridine (**70l**) with 1,2-bis(4-methoxyphenyl)ethyne (**52h**) lead to the formation of **94b** (6,7-bis(4-methoxyphenyl)benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate), which was isolated in 31% yield (Entry 1). Its reaction with 1,2-bis(4-(trifluoromethyl)phenyl)ethyne (**52i**) yielded **94c** (6,7-bis(4-(trifluoromethyl)phenyl)benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate) in 21% isolated yield (Entry 2). Gratifyingly, the same reaction with oct-4-yne (**52j**) gave rise to **94d** (6,7-dipropylbenzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate) in 68% isolated yield (Entry 4). Perhaps, a smaller steric hindrance imparted by the *n*-propyl group in the annulation step can rationalise a higher reaction yield in comparison with substituted diarylethynes.

Table 16. Formation of benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **94**.



70l **52** **94**

Entry	**52**	R	**94**	Yield (%)[a]
1	**52h**	*p*-$MeOC_6H_4$	**94b**	31
2	**52i**	*p*-$CF_3C_6H_4$	**94c**	21
3	**52j**	*n*-Pr	**94d**	68

[a]Isolated yields.

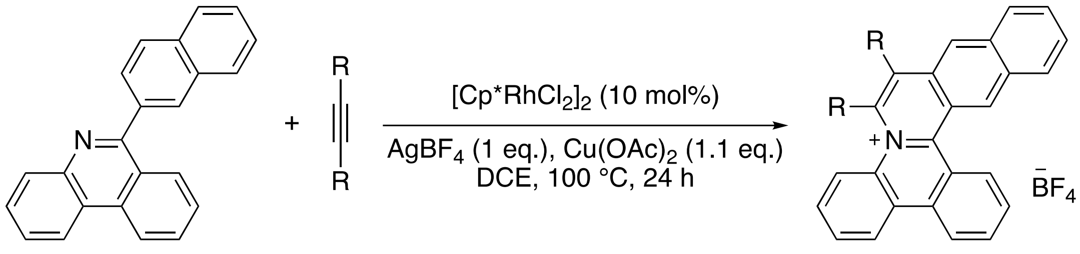
4.4.3. Synthesis of benzo[6,7]isoquinolino[2,1-*f*]phenanthridin-5-ium salts

Next, phenanthridine **70m** was tested in C–H bond activation/annulation sequence with alkynes **52** under previously optimized reaction conditions ([Cp*$RhCl_2]_2$ (10 mol%), $AgBF_4$ (1 eq.) and $Cu(OAc)_2$ (1.1 eq.), DCE, 100 °C, 24 hours) (Table 17). First, a reaction with diphenylethyne (**52a**) provided product **95a** (6,7-diphenylbenzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate) in 67% isolated yield (Entry 1). Next, an annulation with 1,2-bis(4-methoxyphenyl)ethyne (**52h**) furnished product **95b** (6,7-bis(4-methoxyphenyl)benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate) in 76% isolated yield (Entry 2). Outcome of a reaction with 1,2-bis(4-(trifluoromethyl)phenyl)ethyne (**52i**) was slightly worse. The product **95c** (6,7-bis(4-(trifluoromethyl)phenyl)benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate) was isolated in 48% isolated yield (Entry 3). Finally, an annulation with oct-4-yne (**52j**) gave rise to product **95d** with 76% isolated yield (Entry 4).

Surprisingly, the synthesized benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **95** underwent continuous decomposition during column chromatography on silica gel. Currently, it is not clear how the decomposition process proceeds and what kind of products are formed. According to ^{1}H NMR measurements I found that the products **95** decompose to a complex mixture of various substances. Unfortunately, I was not able to separate by column chromatography any individual compound. Therefore, the formation of benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **95** was confirmed only by HRMS analyses.

To sum up, four new benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **95** were prepared in generally good yields, but they could not be obtained in a pure form because of the decomposition process. Therefore, in comparison with 6-(naphth-1-yl)phenanthridine (**70l**) (Chapter 4.4.2), 6-(naphth-2-yl)phenanthridine (**70m**) proved to be better substrate for the C–H bond activation, presumably because the respective C–H bond is less sterically hindered, but the products **95** of C–H bond activation in **70m** are not stable.

Table 17. Formation of benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **95**.



70m **52** **95**

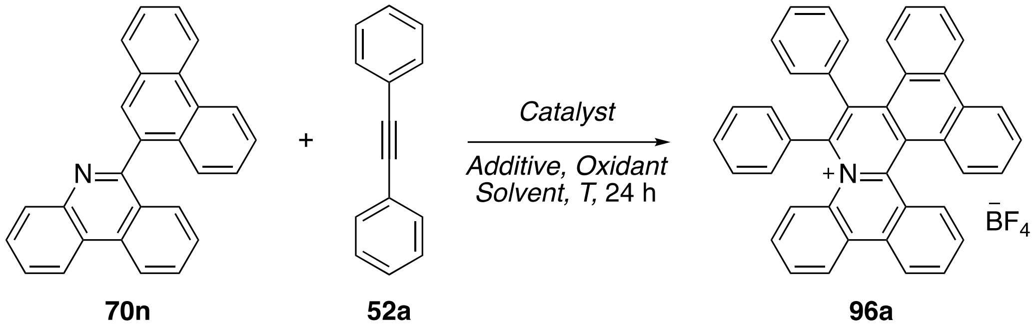
Entry	**52**	R	**95**	Yield (%)[a]
1	**52a**	Ph	**95a**	67
2	**52h**	*p*-$MeOC_6H_4$	**95b**	76
3	**52i**	*p*-$CF_3C_6H_4$	**95c**	48
4	**52j**	*n*-Pr	**95d**	76

[a] Isolated yields.

4.4.4. Synthesis of dibenzo[5,6:7,8]isoquinolino[2,1-*f*]phenanthridin-17-ium salts

C–H bond activation in 6-(phenanthrene-9-yl)phenanthridine (**70n**) proved to be more challenging than in phenanthridines **70l** and **70m**. A testing reaction of phenanthridine **70n** with diphenylethyne (**52a**) under optimized reaction conditions ([Cp*RhCl$_2$]$_2$ (10 mol%) as a catalyst, and AgBF$_4$ (1 eq.), Cu(OAc)$_2$ (1.1 eq.) as additives in DCE at 100 °C for 24 hours) did not proceed as expected (Table 18, Entry 1). According to TLC analyses, some amount of the product was formed, but its separation from the reaction mixture was not successful. Phenanthridine **70n** and diphenylethyne (**52a**) were isolated in almost quantitative amounts. In order to prepare compound **96a** (18,19-diphenyldibenzo[5,6:7,8]isoquinolino[2,1-f]phenanthridin-17-ium tetrafluoroborate), the reaction was carried out using various reaction conditions to achieve C–H bond activation/annulation sequence.^{86} Firstly, as catalyst was used [Rh(COD)$_2$]BF$_4$ (20 mol%) with higher loads of additives (AgBF$_4$ (1.35 eq.), Cu(OAc)$_2$ (2 eq.)) (Entry 2). Unfortunately, the outcome of the reaction did not improve. Some product was again formed, but could not be isolated, and the starting material was recovered in almost quantitative amount. Using [Cp*RhCl$_2$]$_2$ (10 mol%) with slightly modified conditions (NaBF$_4$ (1.35 eq.), Cu(OAc)$_2$ (2 eq.) as additives in MeOH at 100 °C for 24 hours) did not work at all (Entry 3). The starting material was fully recovered from the reaction mixture. The last attempt to synthesize compound **96a** was done using milder reaction conditions ([Cp*RhCl$_2$]$_2$ (10 mol%), with NaBF$_4$ (5 eq.), AgBF$_4$ (3 eq.) as additives in MeOH at 80 °C for 24 hours, Entry 4). The respective TLC analyses showed that some product was formed, but could not be isolated and phenanthridine **70n** with diphenylethyne (**52a**) were isolated in almost quantitative amount from the reaction mixture.

Table 18. Screening of conditions for Rh-catalysed C–H activation/annulation sequence in phenanthridine **70m** with diphenylethyne (**52a**).



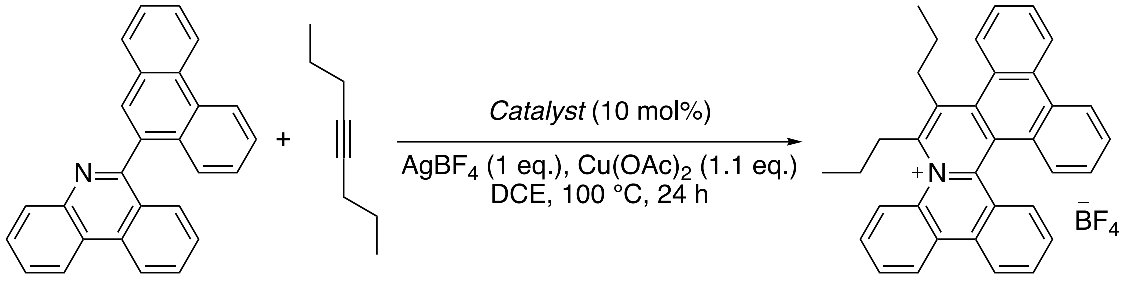
Entry	*Catalyst* (mol%)	*Additive* (eq.)	*T* (°C)	*Oxidant* (eq.)	*Solvent*	Yield (%)[a]
1	$[Cp^*RhCl_2]_2$ (10)	$AgBF_4$ (1)	100	$Cu(OAc)_2$ (1.1)	DCE	0[b]
2	$[Rh(COD)_2]BF_4$ (20)	$AgBF_4$ (1.35)	100	$Cu(OAc)_2$ (2)	DCE	0[b]
3	$[Cp^*RhCl_2]_2$ (10)	$NaBF_4$ (1.35)	100	$Cu(OAc)_2$ (2)	MeOH	0
4	$[Cp^*RhCl_2]_2$ (10)	$NaBF_4$ (5)	80	$AgBF_4$ (3)	MeOH	0[b]

[a] Isolated yields.

[b] Traces of the product.

Since the C–H bond activation in phenanthridine **70n** followed by annulation with diphenylethyne (**52a**) was not successful, I decided to carry out the reaction using less sterically demanding alkyne in the annulation step, oct-4-yne (**52j**) (Table 19). The reaction was initially carried out using the optimized reaction conditions ($[Cp^*RhCl_2]_2$ (10 mol%) as a catalyst, and $AgBF_4$ (1 eq.), $Cu(OAc)_2$ (1.1 eq.) as additives in DCE at 100 °C for 24 hours). The C–H bond activation/annulation process with phenanthridine **70n** was finally achieved, albeit the reaction product **96b** (18,19-dipropyldibenzo[5,6:7,8]isoquinolino[2,1-f]phenanthridin-17-ium tetrafluoroborate) was furnished in a rather low 10% isolated yield (Entry 1). Then I tried to improve the yield of the reaction by using $[Cp^*IrCl_2]_2$ (10 mol%) as a catalyst (Entry 2). However, the product yield dropped and the desired product **96b** was isolated in only 7% yield. When $[Cp^*Co(CO)I_2]$ (10 mol%) was used as a catalyst, the reaction did not proceed at all (Entry 3). The starting material was fully recovered from the reaction mixture.

Table 19. Screening of catalysts for C–H activation in phenanthridine **70n** and annulation with oct-4-yne (**52j**).



70n **52j** **96b**

Entry	*Catalyst*	Yield (%)[a]
1	$[Cp^*RhCl_2]_2$	10
2	$[Cp^*IrCl_2]_2$	7
3	$[Cp^*Co(CO)I_2]$	0

[a] Isolated yields.

By the time of the submission of diploma thesis, the product **96b** could not be isolated in a sufficiently pure form to record relevant ^{1}H and ^{13}C NMR spectra as well as IR spectra. The formation of the product **96b** was so far confirmed by HRMS analysis.

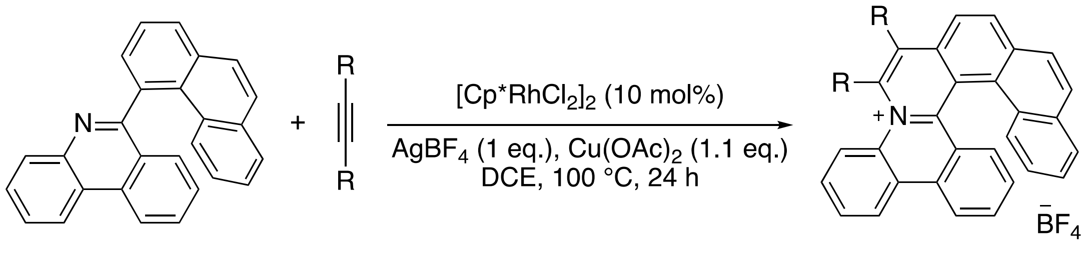
To sum up, the C–H bond activation in 6-(phenanthrene-9-yl)phenanthridine (**70n**) was not successful using diphenylacetylene (**52a**) in the annulation step. When oct-4-yne (**52j**) was used, the product **96b** was formed in the isolated yield of 10%. These findings imply that the C–H bond activation using 6-(phenanthrene-9-yl)phenanthridine (**70n**) and followed annulation proceeds with less sterically demanding alkynes **52**. In addition, in comparison with phenanthridines **70l** (Chapter 4.4.2) and **70m** (Chapter 4.4.3), 6-(phenanthrene-9-yl)phenanthridine (**70n**) was the least reactive towards C–H bond activation. Perhaps, the bulkiness of phenanthrene-9-yl group is the reason for such reactivity.

4.4.5. Synthesis of naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts

Lastly, 6-(phenanthren-4-yl)phenanthridine (**70o**) was subjected to catalytic C–H bond activation/annulation reaction sequence with alkynes **52**. The following optimized reaction conditions were used: $[Cp^*RhCl_2]_2$ (10 mol%), $AgBF_4$ (1 eq.) and $Cu(OAc)_2$ (1.1 eq.), DCE, 100 °C for 24 hours (Table 20).

Firstly, annulation with diphenylacetylene (**52a**) furnished the product **97a** (6,7-diphenylnaphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate) in 51% isolated yield (Entry 1). Then annulation reactions of **70o** with alkynes **52h**, **52i** and **52j** provided products **97** with lower yields in the range of 20-31%. The annulation with 1,2-bis(4-methoxyphenyl)ethyne (**52h**) provided product **97b** (6,7-bis(4-methoxyphenyl)naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate) in 31% isolated yield (Entry 2). The annulation with 1,2-bis(4-(trifluoromethyl)phenyl)ethyne (**52i**) gave product **97c** (6,7-bis(4-(trifluoromethyl)phenyl)naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate) in 21% isolated yield (Entry 3). Finally, the annulation reaction with oct-4-yne (**52j**) gave rise to product **97d** (6,7-dipropylnaphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate) in 20% yield (Entry 4).

Table 20. Formation of naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts **97**.



70o **52** **97**

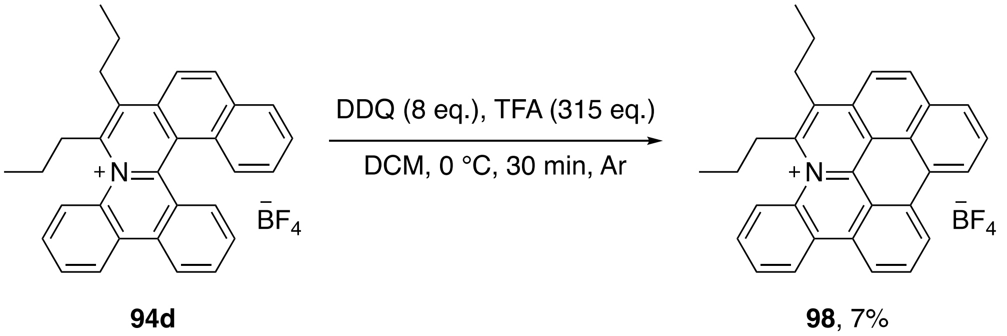
Entry	**52**	R	**97**	Yield (%)[a]
1	**52a**	Ph	**97a**	51
2	**52h**	*p*-$MeOC_6H_4$	**97b**	31
3	**52i**	*p*-$CF_3C_6H_4$	**97c**	21
4	**52j**	*n*-Pr	**97d**	20

[a] Isolated yields.

To summarize the results, the synthesis of four new compounds with the [6]helical scaffold, naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts **97**, was accomplished by catalytic C–H activation/annulation sequence of phenanthridine **70o**. Surprisingly, the reactions of phenanthridine **70o** with diarylalkynes **52** furnished the respective products **52** in similar (or somewhat better) yields than the reactions of a structurally related phenanthridine **70l** bearing the less bulky naphthyl group (Chapter 4.4.2). At the moment there is not available any reasonable explanations for this phenomenon.

4.5. Scholl reaction

The Scholl reaction is used for coupling of aromatic rings by using only a Lewis acid and a protic acid. The published conditions I decided to use were as follows: DDQ (8 eq.), TFA (315 eq.) in DCM at 0 °C for 30 min under argon atmosphere.[87] The main reason was that these conditions did not require high reaction temperature and the reaction should be finished in 30 min. The substrate, 6,7-dipropylbenzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate (**94d**), was chosen because there is only one possibility of ring closure. The ring closure was indeed successful and the product **98** (14,15-dipropylnaphtho[2',1',8':4,5,6]quinolino[1,8,7-fgh]phenanthridin-13-ium tetrafluoroborate) was formed with 7% isolated yield (Scheme 38).



Scheme 38. Scholl reaction of **94d**.

By the time of the submission of diploma thesis, the product **98** was not prepared in a sufficient amount to record ^{1}H and ^{13}C NMR spectra as well as IR spectra. The formation of the product **98** was so far confirmed by HRMS analysis.

Even though the yield of the reaction was not satisfactory, the reaction confirmed the possibility that the prepared cationic helical *N*-heterocycles can undergo the Scholl reaction and form compounds with extended π-conjugated systems. The obtained result opens new area for further research.

4.6. Absorption and emission spectra

Absorption spectra of benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **94** and naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts **97** were recorded and are depicted in Chart 1.

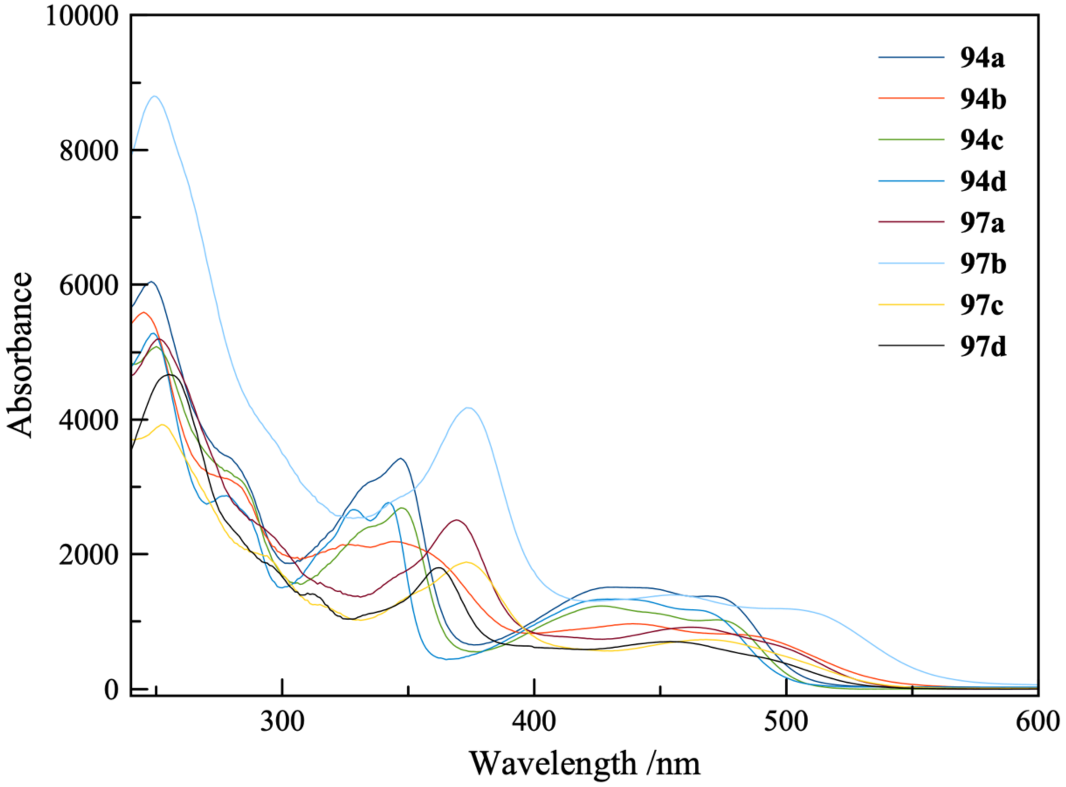


Chart 1. Absorption spectra of compounds **94** and **97** measured in DCM solutions ($c = 10^{-5}$ M).

Then, emission spectra of compounds **94** and **97** were recorded (Chart 2, Table 21). Four samples of benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **94** bearing various substituents were measured. The phenyl substituted compound **94a** emitted in the green region of the visible spectrum (537 nm) with a quantum yield of Φ = 6%. The compound with the *p*-methoxyphenyl group **94b** emitted in the orange region of the visible spectrum (623 nm) with a quantum yield of Φ = 14%. The salt **94c** bearing the electron-withdrawing *p*-(trifluoromethyl)phenyl group had again emission in the green region of visible spectrum (525 nm) with a quantum yield of Φ = 6%. Compound **94d** with the *n*-propyl groups did not exhibit any emission, therefore it is not included in the

Chart 2. Four samples of naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts **97** bearing various substituents were measured. The phenyl substituted compound **97a** had emission in the yellow region of the visible spectrum (575 nm) with a quantum yield of Φ = 8%. Compound **97b** with the electron-donating *p*-methoxyphenyl groups mitted in in the orange region of the visible spectrum (616 nm) with a quantum yield of Φ = 20%. Compound **97c** bearing the electron-withdrawing *p*-(trifluoromethyl)phenyl groups had emission was in the yellow region of the visible spectrum (578) with a quantum yield of Φ = 7%. Once again, compound **97d** with *n*-propyl substitution did not exhibit any emission, therefore is not included in the Chart 2.

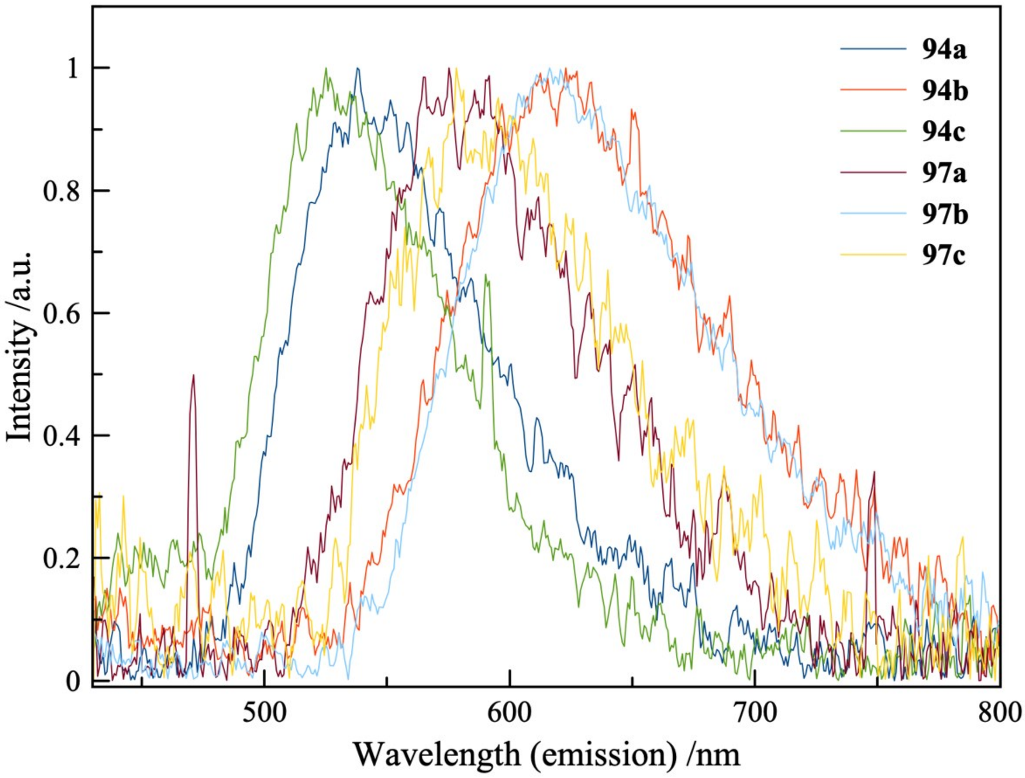


Chart 2. Normalized emission spectra of compounds **94** and **97**.

In summary, it was found out that the electron-donating *p*-methoxyphenyl group in **94b** and **97b** enhances the emission. Also, naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts **97** with the [6]helical scaffold provided slightly better quantum yields of emission than benzo[7,8]isoquinolino[2,1-*f*]phenanthridine-5-ium salts **94** with the [5]helical scaffold.

Table 21. Wavelength of maximum emission and quantum yield of compounds **94** and **97**.

94 or **97**	R	$\lambda_{\text{ems}}{}^{a}$ (nm)	$\Phi_{\text{abs}}{}^{a}$ (%)
94a	Ph	537	6
94b	p-$MeOC_6H_4$	623	14
94c	p-$CF_3C_6H_4$	525	6
94d	n-Pr	–	0
97a	Ph	575	8
97b	p-$MeOC_6H_4$	616	20
97c	p-$CF_3C_6H_4$	578	7
97d	n-Pr	–	0

[a]Measured in DCM solutions ($c = 10^{-6}$ M).

5. Experimental Section

5.1. General

All commercially available reagents were purchased from available sources (Fluorochem, Sigma Aldrich, Alfa Aesar, Acros Organics, PENTA and Strem Chemicals) and were used without further purification. Solvents were purified and dried by distillation as follows: dichloromethane from calcium hydride, tetrahydrofuran from sodium/benzophenone, or by molecular sieves: *N*,*N*-dimethylformamide. Ethyl acetate, hexane and dichloromethane used for column chromatography were distilled.

The reactions were monitored by using thin layer chromatography (TLC) which was performed on SiliCycle silica gel 60 F_{254} coated aluminium plates. Compounds were visualised by UV lamp (254 nm). Column chromatography was performed on SiliCycle silica gel 60 (0,040–0,063 mm).

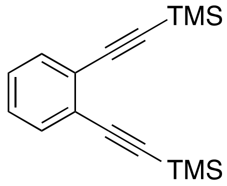
NMR spectra were recorded on Bruker Avance III HD 400 spectrometer (400.13 MHz for ^{1}H, 100.61 MHz for ^{13}C) or on Bruker Avance III HD 600 spectrometer (600.17 MHz for ^{1}H, 150.04 for ^{13}C). NMR spectra were recorded in $CDCl_3$ at 25 °C. Chemical shifts are given in δ scale listed in ppm, and were referenced to a residual $CDCl_3$ signal (^{1}H, $\delta = 7.26$ ppm; ^{13}C, $\delta = 77.16$ ppm) or to a residual $(CD_3)_2CO$ signal (^{1}H, $\delta = 2.05$ ppm; ^{13}C, $\delta = 29.84, 206.26$ ppm). Coupling constants J are given in Hz, and multiplicity is defined as follows: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, or the combination of above-mentioned. NMR spectra were processed by MestReNova program.

Infrared spectra were recorded using two methods. First method is measurement by Thermo Nicolet AVATAR 370 FT-IR spectrometer using KBr tablets of the compounds via DRIFT method and IR spectra are reported in wave numbers (cm^{-1}). Second method is measurement by Vertex 70v FT-IR spectrometer using powder of the compounds and IR spectra are reported in wave numbers (cm^{-1}). Mass spectra were recorded on compact^{TM} ESI QTOF Mass Spectrometer (Bruker Daltonics). Absorption UV/VIS spectra were recorded on SPECORD 50 PLUS. Emission spectra were recorded on Hamamatsu Quantaurus-QY Plus UV-NIR absolute quantum yield spectrometer C13534 ($\lambda_{exc} = 330$ nm).

5.2. Synthesis of starting material

5.2.1. Synthesis of biphenylene

Bis((trimethylsilyl)ethynyl)benzene (82).

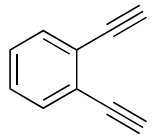


1,2-Dibromobenzene (**80**) (40.0 mmol, 9.44 g) was dissolved in diisopropylamine (80 mL). The solution was bubbled with argon in a round bottom pressure flask. To a stirred solution, trimethylsilylacetylene (**81**) (240 mmol, 36.0 mL), CuI (4.00 mmol, 0.762 g) and $Pd(PPh_3)_4$ (2.00 mmol, 2.31 g) were added. The reaction mixture was heated at 100 °C for 24 h. After that, the reaction was left stirring at 25 °C overnight. Then the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane → 20/1, hexane/EtOAc) provided 10.5 g (97%) of the title compound as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (dd, *J* = 5.8, 3.4 Hz, 2H), 7.24 (dd, *J* = 5.8, 3.3 Hz, 2H), 0.28 (s, 18H).

The recorded spectral data were in agreement with the published data.[88]

1,2-Diethynylbenzene (83).

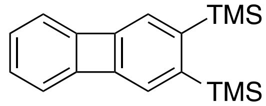


Bis((trimethylsilyl)ethynyl)benzene (**82**) (38.8 mmol, 10.5 g) was dissolved in a mixture of methanol and chloroform (2×20 mL), and K_2CO_3 (155 mmol, 22.1 g) was added to a stirred solution. The reaction mixture was left at 25 °C for 3 h. Then volatiles were removed under reduced pressure and the residue was dissolved in DCM (20 mL) and HCl (10%) was added until the pH of the mixture was in the acidic region. The reaction mixture was then extracted by DCM (3×50 mL), the combined organic layers were dried over anhydrous Na_2SO_4, volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane → 20/1, hexane/EtOAc) provided 4.41 g (90%) of the title compound as a slightly red liquid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 (dd, *J* = 5.7, 3.4 Hz, 2H), 7.30 (dd, *J* = 5.8, 3.4 Hz, 2H), 3.36 (s, 2H).

The recorded spectral data were in agreement with the published data.[88]

2,3-Bis(trimethylsilyl)biphenylene (85).

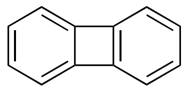


Bis(trimethylsilyl)acetylene (**84**) (BTSA, 232 mmol, 50.0 mL) was heated in a three-neck flask under argon atmosphere to 140 °C. Then a solution of 1,2-diethynylbenzene (**83**) (12.2 mmol, 1.54 g) and $CpCo(CO)_2$ (1.22 mmol, 0.162 mL) in BTSA **84** (116 mmol, 25.0 mL) was added to into it in portions of 2.5 mL every 10 minutes. During the course of the reaction, the flask was irradiated with a lamp (300 W), which was placed as close to the centre of the flask as possible. After 2 h, the reaction was left to cool down to 25 °C and remaining BTSA was evaporated under reduced pressure. Column chromatography of the residue on silica gel (hexane) provided 2.89 g (80%) of the title compound as a yellow oil. The reaction was repeated twice and the product **85** was isolated in 77% and 81% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.01 (s, 2H), 6.79–6.73 (m, 2H), 6.72–6.67 (m, 2H), 0.38 (s, 18H).

The recorded spectral data were in agreement with the published data.[89]

Biphenylene (65).



2,3-Bis(trimethylsilyl)biphenylene (**85**) (9.70 mmol, 2.88 g) was dissolved in DCM (20 mL) and to a stirring solution was added trifluoroacetic acid (194 mmol, 14.8 mL) in one portion. The reaction mixture was left stirring at 25 °C for 2 h. Then small amount of water (5 mL) was added. The reaction mixture was extracted with DCM (3×20 mL), the combined organic layers were dried over anhydrous Na_2SO_4, volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane) provided 1.33 g, (90%) of the title compound as a colourless solid. The reaction was repeated twice and the product **65** was isolated with 79% and 96% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 6.76–6.70 (m, 4H), 6.65–6.60 (m, 4H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 151.5, 128.4, 117.5.

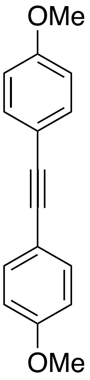
The recorded spectral data were in agreement with the published data.[90]

5.2.2. Synthesis of substituted diphenylalkynes

General procedure.

$PdCl_2(PPh_3)_2$ (0.42 mmol, 295 mg), CuI (0.70 mmol, 133 mg) and an aryl iodide **93** (7.00 mmol) were dissolved in dry benzene (35 mL) in a round bottom pressure flask. DBU (42.0 mmol, 6.27 mL) is then added by syringe. While stirring, the reaction mixture was bubbled with argon. After that, ice-chilled trimethylsilylethylene (**81**) (3.50 mmol, 0.48 mL) was added followed immediately by distilled water (0.05 mL). The reaction mixture was left stirring at 25 °C or 60 °C for 18 h. Then the reaction mixture was partitioned between diethyl ether (50 mL) and distilled water (50 mL). The organic layer was washed with HCl (10%, 3×75 mL), saturated aqueous solution of NaCl (75 mL), dried over anhydrous Na_2SO_4 and volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel provided the respective products.

1,2-Bis(4-methoxyphenyl)ethyne (52h).



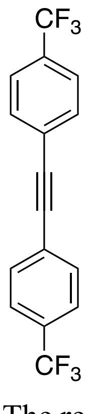
1-Iodo-4-methoxybenzene (**93a**) (7.00 mmol, 1.64 g) was used, the reaction was carried out at 60 °C. Column chromatography of the residue on silica gel (hexane/EtOAc, 40/1 → 20/1) provided 0.53 g (63%) of the title compound as a yellow powder.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (d, *J* = 8.8 Hz, 4H), 6.87 (d, *J* = 8.9 Hz, 4H), 3.83 (s, 6H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 159.5, 133.0, 115.9, 114.1, 88.1, 55.4.

The recorded spectral data were in agreement with the published data.[85]

1,2-Bis(4-(trifluoromethyl)phenyl)ethyne (52i).



1-Iodo-4-(trifluoromethyl)benzene (**93b**) (7.00 mmol, 1.00 mL) was used, the reaction carried out at 25 °C. Column chromatography of the residue on silica gel (hexane → 70/1, hexane/EtOAc) provided 0.99 g (90%) of the title compound as a colourless powder.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68–7.61 (m, 8H);

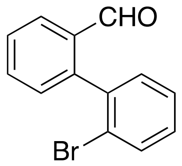
^{13}C NMR (101 MHz, $CDCl_3$) δ 132.1, 130.7 (q, *J* = 32.7 Hz), 126.5, 125.6 (q, *J* = 3.9 Hz), 124.0 (q, *J* = 271.3 Hz), 90.3.

The recorded spectral data were in agreement with the published data.[91]

5.2.3. Synthesis of phenanthren-4-ylboronic acid

2'-Bromo-[1,1'-biphenyl]-2-carbaldehyde (91).

2-Bromobenzaldehyde (**89**) (1.71 mmol, 0.20 mL), 2-bromophenylboronic acid (**69f**) (2.05 mmol, 412 mg), $Pd(PPh_3)_4$ (44.0 μmol, 51.4 mg) and K_2CO_3 (8.00 mmol, 1.11 g) were dissolved in THF (5 mL) and distilled water (1 mL). Stirred reaction mixture was bubbled with argon and heated at 90 °C for 24 h. After cooling down to 25 °C volatiles were removed under reduced pressure. The residue was dissolved in EtOAc (10 mL) and partitioned between EtOAc (20 mL) and distilled water (20 mL). The aqueous phase was extracted with EtOAc (3×20 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (40:1 → 20/1 hexane/EtOAc,) provided 333 mg (75%) of the title compound as a yellow oil. The reaction was done once more in 75% yield.



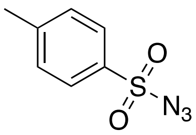
^{1}H NMR (400 MHz, $CDCl_3$) δ 9.79 (s, 1H), 8.04 (dd, J = 7.8, 1.3 Hz, 1H), 7.71–7.64 (m, 2H), 7.58–7.53 (m, 1H), 7.44–7.39 (m, 1H), 7.35–7.29 (m, 3H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 191.7, 144.6, 139.0, 133.82, 133.78, 132.9, 131.7, 131.0, 130.0, 128.7, 127.53, 127.50, 123.98.

The recorded spectral data were in agreement with the published data.[92]

Ohira-Bestmann reagent (63).

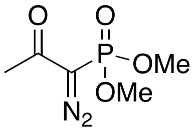
TsCl (42.0 mmol, 8.00 g) and NaN_3 (42.0 mmol, 2.73 g) were dissolved in acetone (120 mL) and distiller water (120 mL). The reaction mixture was left stirring at 0 °C for 2 h. After that, acetone was removed under reduced pressure and the reaction mixture was extracted with diethyl ether (3×50 mL). The combined organic layers were dried over anhydrous Na_2SO_4. Volatiles were removed under reduced pressure yielding 7.87 g (95%) of depicted tosyl azide as a colourless liquid.



^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, J = 8.5 Hz, 2H), 7.40 (d, J = 8.1 Hz, 2H), 2.47 (s, 3H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 146.3, 135.5, 130.4, 127.6, 21.8.

The recorded spectral data were in agreement with the published data.[93]



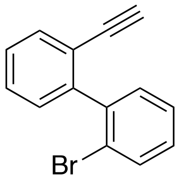
NaH (60% dispersion in mineral oil, 7.90 mmol, 316 mg) was dissolved in dry THF (19.2 mL) and the solution was cooled down to 0 °C. To a stirring reaction mixture, a solution of dimethyl-(2-oxopropyl)phosphonate (7.20 mmol, 1.00 mL) in dry THF (19.2 mL) was added dropwise. After stirring at 0 °C for 1 h, tosyl azide (7.90 mmol, 1.56 g) was added. The resulting mixture was left stirring at 0 °C for 30 min. Then the reaction mixture was passed through a short column of silica gel (EtOAc) to give 1.34 g (97%) of Ohira-Bestman reagent as an orange oil. The reaction was done once more in 97% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.82 (s, 3H), 3.79 (s, 3H), 2.22 (s, 3H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 190.0, 189.9, 53.7, 53.6, 27.2.

The recorded spectral data were in agreement with the published data.[94]

2-Bromo-2'-ethynyl-1,1'-biphenyl (92).



2'-Bromo-[1,1'-biphenyl]-2-carbaldehyde (**91**) (0.36 mmol, 94.0 mg), Ohira-Bestmann reagent **63** (1.84 mmol, 354 mg) and K_2CO_3 (0.74 mmol, 102 mg) were suspended in dry MeOH (3 mL). The reaction mixture was left stirring at 25 °C for 48 h. Volatiles were removed under reduced pressure. The residue was dissolved in DCM (10 mL) and partitioned between DCM (20 mL) and the saturated aqueous solution of NaCl (20 mL). The aqueous phase was extracted with DCM (3×20 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane) provided 67.6 mg (73%) of the title compound as a pale yellow oil. The reaction was repeated multiple times with isolated yields in the range of 48–73%.

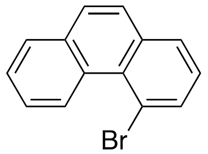
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68 (dd, J = 8.0, 1.0 Hz, 1H), 7.62 (dd, J = 7.4, 1.4 Hz, 1H), 7.45–7.32 (m, 4H), 7.30–7.22 (m, 2H), 2.95 (s, 1H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 144.2, 141.5, 133.0, 132.7, 131.4, 129.9, 129.3, 128.6, 127.8, 127.1, 123.5, 121.8, 82.3, 80.5.

The recorded spectral data were in agreement with the published data.[95]

4-Bromophenanthrene (90).

2-Bromo-2'-ethynyl-1,1'-biphenyl (**92**) (0.95 mmol, 245 mg) was dissolved in DCE (5 mL) and the solution was bubbled with argon. $PtCl_2$ (76.0 µmol, 20.2 mg) was added and the reaction was heated at 100 °C for 24 h. After cooling down to 25 °C, the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane) provided 158 mg (65%) of the title compound as a pale yellow oil. The reaction was repeated twice in 51% and 64% isolated yields.



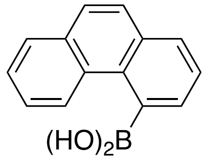
^{1}H NMR (400 MHz, $CDCl_3$) δ 10.08–10.04 (m, 1H), 8.00 (dd, *J* = 7.7, 1.4 Hz, 1H), 7.93–7.87 (m, 1H), 7.85 (dd, *J* = 7.9, 1.3 Hz, 1H), 7.75 (d, *J* = 8.8 Hz, 1H), 7.70–7.62 (m, 3H), 7.38 (t, *J* = 7.7 Hz, 1H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 135.3, 134.8, 133.5, 129.9, 129.0, 128.73, 128.65, 128.4, 127.3, 127.2, 126.9, 126.7, 125.5, 119.7.

The recorded spectral data were in agreement with the published data.[95]

Phenanthren-4-ylboronic acid (69e).

4-Bromophenanthrene (**90**) (0.95 mmol, 244 mg) was dissolved in dry THF (4 mL) under argon atmosphere. The solution was cooled down to –78 °C (dry ice/acetone bath). Then, 1.7 M solution of *t*-BuLi in pentane (1.00 mmol, 0.60 mL) was added dropwise and the reaction mixture was left stirring for 45 min. Formation of white precipitate was observed. After that, $B(OMe)_3$ (1.00 mmol, 0.11 mL) was added. The resulting clear solution was left stirring at –78 °C for 1 h. The reaction mixture was then allowed to warm to 25 °C and stirring was continued for 3 h. Then, 10% solution of HCl (2.00 mL) was added. The reaction mixture was extracted with EtOAc (3×20 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and volatiles were removed under reduced pressure. The residue was suspended in hexane (30 mL) and filtered to give 200 mg (95%) of the title compound as a colourless powder.



The phenanthren-4-ylboronic acid (**69e**) was used in the next step without further purification.

M.p. 119-124 °C;

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.79–8.74 (m, 1H), 7.98–7.94 (m, 1H), 7.91 (dd, *J* = 7.9, 1.5 Hz, 1H), 7.80 (s, 2H), 7.74–7.70 (m, 1H), 7.65–7.49 (m, 5H);

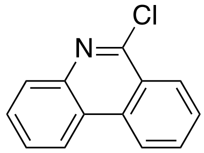
^{13}C NMR (101 MHz, $CDCl_3$) δ 133.7, 133.1, 132.3, 131.6, 129.7, 129.4, 128.5, 128.15, 128.14, 127.6, 127.1, 126.7, 126.6, 126.4;

IR (KBr) ν_{max} 3284, 1336, 1292, 1020, 829, 806, 789, 739, 721, 673, 650, 636, 538, 472 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{16}H_{15}BNaO_2$ $[M+Na]^+$ 273,1057, found 273.1057.

5.2.4. Synthesis of 6-chlorophenanthridine

6-Chlorophenanthridine (68).



Phenanthridin-6(5*H*)-one (**86**) (15.4 mmol, 3.01 g) was dissolved in $POCl_3$ (154 mmol, 14.3 mL) and anhydrous *N*,*N*-dimethylaniline (7.89 mmol, 1.00 mL) was added. The reaction mixture was heated under reflux for 3 h while stirring. After cooling down to 25 °C, the reaction mixture was poured over ice and extracted by DCM (4×30 mL). The combined organic layers were washed with saturated aqueous solution of Na_2CO_3 (2×30 mL), dried over anhydrous Na_2SO_4, and volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane/EtOAC, 40/1 → 20/1) provided 3.02 g (92%) of the title compound as a colourless powder.

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.61 (d, *J* = 8.3 Hz, 1H), 8.53 (dd, *J* = 8.1, 1.4 Hz, 1H), 8.49 (dd, *J* = 8.3, 0.8 Hz, 1H), 8.10 (dd, *J* = 8.2, 1.3 Hz, 1H), 7.91 (ddd, *J* = 8.4, 7.1, 1.3 Hz, 1H), 7.80–7.72 (m, 2H), 7.69 (ddd, *J* = 8.2, 7.2, 1.6 Hz, 1H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 151.6, 143.5, 134.7, 131.9, 129.52, 129.50, 128.4, 127.9, 127.6, 125.1, 124.2, 122.44, 122.37.

The recorded spectral data were in agreement with the published data.[96]

5.3. Synthesis of substituted phenanthridines

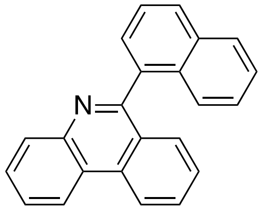
General procedure for C–C bond cleavage (A).

Biphenylene (**65**) (1.00 mmol, 152 mg), nitrile **75f** or **75g** (10.0 mmol, 1.53 g), [Rh(COD)$_2$BF$_4$] (0.10 mmol, 40.6 mg) and dppe (0.10 mmol, 39.8 mg) were dissolved in dry THF (5 mL). The reaction mixture in a microwave vial was bubbled with argon and heated in a microwave reactor at 180 °C or 200 °C for 2 h. Then volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane/EtOAc, 40:1 → 10/1) provided the respective products.

General procedure for Suzuki-Miyaura cross-coupling (B).

6-Chlorophenanthridine (**68**) (0.63 mmol, 135 mg), arylboronic acid **69** (0.63 mmol), Pd(PPh$_3$)$_4$ (1.26 μmol, 1.46 mg) were dissolved in THF (10 mL). Then a solution of K$_2$CO$_3$ (2M, 2.00 mL) was added and while stirring the reaction mixture was bubbled with argon. The reaction was kept under reflux for 6 or 8 h. After cooling down to 25 °C volatiles were removed under reduced pressure. The residue was dissolved in DCM (10 mL) and partitioned between DCM (20 mL) and distilled water (20 mL). The aqueous phase was extracted with DCM (3×20 mL). The combined organic layers were dried over anhydrous Na$_2$SO$_4$ and volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (hexane/EtOAc, 40:1 → 10/1) provided the respective products.

6-(Naphthalen-1-yl)phenanthridine (70l).



General procedure **A**. 1-Naphthonitrile (**75f**) (10.0 mmol, 1.53 g) was used. The reaction was carried out at 180 °C. Column chromatography of the residue on silica gel provided 9.2 mg (3%) of the title compound as a colourless powder.

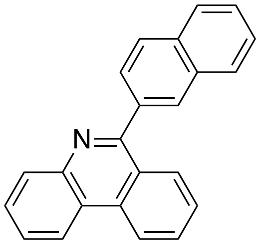
General procedure **B**. Naphthalen-1-ylboronic acid (**69c**) (0.63 mmol, 108 mg) was used. The reaction time was 6 h. Column chromatography of the residue on silica gel provided 164 mg (85%) of the title compound as a colourless powder.

^{1}H NMR (400 MHz, CDCl$_3$) δ 8.74 (d, J = 8.4 Hz, 1H), 8.70 (dd, J = 8.2, 1.5 Hz, 1H), 8.33 (dd, J = 8.2, 1.3 Hz, 1H), 8.04 (dd, J = 7.4, 1.8 Hz, 1H), 7.98 (d, J = 8.2 Hz, 1H), 7.87–7.79 (m, 2H), 7.75 (ddd, J = 8.3, 7.1, 1.5 Hz, 1H), 7.71–7.64 (m, 3H), 7.53–7.44 (m, 3H), 7.32 (ddd, J = 8.2, 6.7, 1.2 Hz, 1H);

^{13}C NMR (150 MHz, CDCl$_3$) δ 161.2, 143.9, 137.1, 133.9, 133.3, 132.5, 131.0, 130.5, 129.4, 129.2, 128.5, 127.6, 127.5, 127.4, 126.7, 126.6, 126.20, 126.18, 125.5, 124.2, 122.3, 122.2.

The recorded spectral data were in agreement with the published data.[97]

6-(Naphthalen-2-yl)phenanthridine (70m).



General procedure **A**. 2-Naphthonitrile (**75 g**) (10.0 mmol, 1.53 g) was used. The reaction was carried out at 200 °C. Column chromatography of the residue on silica gel provided 189 mg (62%) of the title compound as a slightly yellow powder.

M.p. 146-147 °C;

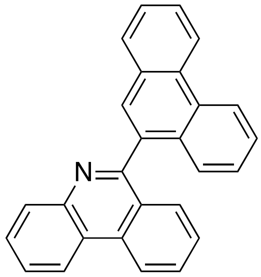
^{1}H NMR (400 MHz, CDCl$_3$) δ 8.75 (d, J = 8.3 Hz, 1H), 8.66 (d, J = 8.1 Hz, 1H), 8.34 (br s, 1H), 8.25 (s, 1H), 8.17 (d, J = 8.2 Hz, 1H), 8.05 (d, J = 8.3 Hz, 1H), 8.00–7.94 (m, 2H), 7.92–7.85 (m, 2H), 7.80 (t, J = 7.4 Hz, 1H), 7.73 (t, J = 7.7 Hz, 1H), 7.63 (t, J = 7.7 Hz, 1H), 7.61–7.55 (m, 2H);

^{13}C NMR (150 MHz, CDCl$_3$) δ 161.3, 143.7, 136.9, 133.8, 133.6, 133.3, 131.0, 130.3, 129.6, 129.3, 129.2, 128.7, 128.3, 128.0, 127.50, 127.45, 127.3, 126.8, 126.6, 125.5, 124.0, 122.4, 122.2;

IR (KBr) $\nu_{\max}$ 850, 822, 814, 758, 741, 723, 714, 681, 478, 428 cm^{-1};

HRMS (ESI) m/z calculated for $C_{23}H_{16}N$ [M+H]$^+$ 306.1277, found 306.1281.

6-(Phenanthren-9-yl)phenanthridine (70n).



General procedure **B**. Phenanthren-9ylboronic acid (**69d**) (0.63 mmol, 140 mg) was used. The reaction time was 8 h. Column chromatography of the residue on silica gel provided 179 mg (80%) of the title compound as a colourless powder.

M.p. 243-244 °C;

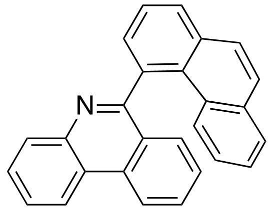
^{1}H NMR (400 MHz, CDCl$_3$) δ 8.86–8.78 (m, 2H), 8.76 (d, J = 8.3 Hz, 1H), 8.72 (dd, J = 8.0, 1.5 Hz, 1H), 8.35 (d, J = 7.8 Hz, 1H), 7.97 (s, 1H), 7.95 (dd, J = 7.9, 1.2 Hz, 1H), 7.88–7.72 (m, 5H), 7.70–7.64 (m, 2H), 7.50–7.44 (m, 2H), 7.40 (ddd, J = 8.0, 6.9, 1.1 Hz, 1H);

^{13}C NMR (101 MHz, CDCl$_3$) δ 161.1, 143.9, 135.9, 133.2, 131.5, 131.4, 131.1, 130.8, 130.7, 130.5, 129.3, 129.2, 129.1, 128.6, 127.51, 127.45, 127.3, 127.14, 127.08, 126.90, 126.88, 126.7, 124.2, 123.1, 122.8, 122.3, 122.2;

IR (KBr) ν_{max} 1566, 1448, 1356, 760, 748, 726, 615, 548, 503, 434 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{27}H_{18}N$ $[M+H]^+$ 356.1434, found 356.1436.

6-(Phenanthren-4-yl)phenanthridine (70o).



General procedure **B**. Phenanthren-4-ylboronic acid (**69e**) (0.63 mmol, 140 mg) was used. The reaction time was 8 h. Column chromatography of the residue on silica gel provided 76.1 mg (34%) of the title compound as a colourless powder.

M.p. 93-98 °C;

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.73 (d, *J* = 8.3 Hz, 2H), 8.33 (d, *J* = 7.8 Hz, 1H), 8.09 (dd, *J* = 7.8, 1.5 Hz, 1H), 7.89 (d, *J* = 8.8 Hz, 1H), 7.85–7.72 (m, 6H), 7.68 (dd, *J* = 7.2, 1.6 Hz, 1H), 7.48 (dd, *J* = 8.2, 0.8 Hz, 1H), 7.36–7.29 (m, 3H), 6.83 (ddd, *J* = 8.6, 7.0, 1.5 Hz, 1H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 164.7, 144.2, 137.2, 133.6, 133.4, 133.3, 131.1, 130.61, 130.55, 130.1, 129.9, 129.4, 129.1, 128.7, 128.0, 127.7, 127.4, 127.1, 126.20, 126.15, 125.9, 124.2, 122.3, 122.2;

IR (KBr) ν_{max} 1294, 829, 760, 741, 725, 710, 683, 613, 496, 440 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{27}H_{18}N$ $[M+H]^+$ 356.1434, found 356.1431.

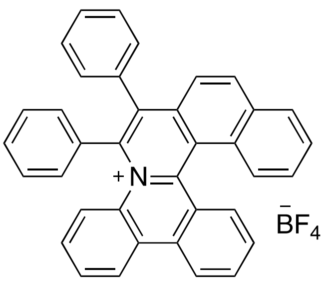
5.4. C–H bond activation in phenanthridines

General procedure.

Phenanthridine **70** (0.30 mmol), alkyne **52** (0.30 mmol), [Cp*RhCl$_2$]$_2$ (0.03 mmol, 18.5 mg), AgBF$_4$ (0.30 mmol, 58.4 mg) and Cu(OAc)$_2$ (0.33 mmol, 59.9 mg) were dissolved in DCE (5 mL). Stirring reaction mixture was heated at 100 °C for 24 h. After cooling down to 25 °C, the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (DCM/MeOH, 100/1 → 20/1) provided the respective products. The products were further purified by precipitation from DCM solutions with cyclohexane.

5.4.1. Synthesis of benzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium salts

6,7-Diphenylbenzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate (94a).



6-(Naphthalen-1-yl)phenanthridine (**70l**) (0.30 mmol, 91.6 mg) and diphenylethyne (**52a**) (0.30 mmol, 53.5 mg) were used. Column chromatography of the residue on silica gel provided 49.5 mg (29%) of the title compound as a yellow solid. Precipitation provided 23.3 mg (14%) of the title compound as a yellow powder.

M.p. ~ 300 °C;

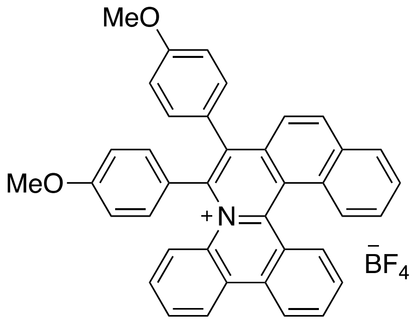
^{1}H NMR (600 MHz, CDCl$_3$) δ 8.68 (d, *J* = 7.5 Hz, 1H), 8.64 (d, *J* = 8.0 Hz, 1H), 8.61 (d, *J* = 7.8 Hz, 1H), 8.52 (d, *J* = 7.2 Hz, 1H), 8.30 (d, *J* = 8.8 Hz, 1H), 8.10 (t, *J* = 6.9 Hz, 1H), 8.07 (d, *J* = 7.9 Hz, 1H), 7.96 (d, *J* = 6.5 Hz, 1H), 7.85 (d, *J* = 5.4 Hz, 1H), 7.80–7.70 (m, 3H), 7.68 (t, *J* = 6.3 Hz, 1H) 7.63 (t, *J* = 6.7 Hz, 1H), 7.60 (br s, 1H), 7.52 (t, *J* = 7.0 Hz, 1H), 7.43–7.34 (m, 2H), 7.23 (br s, 2H), 7.16 (t, *J* = 7.1 Hz, 1H), 7.09 (br s, 1H), 6.74 (d, *J* = 6.5 Hz, 1H), 6.71 (d, *J* = 7.0 Hz, 1H);

^{13}C NMR (150 MHz, CDCl$_3$) δ 153.4, 145.9, 139.1, 138.6, 136.9, 135.9, 135.1, 134.1, 133.8, 133.7, 133.2, 132.8, 131.2, 130.6, 130.4, 130.32, 130.27, 129.9, 129.73, 129.65, 129.3, 129.1, 129.0, 128.94, 128.88, 128.77, 128.5, 127.7, 127.0, 125.9, 124.5, 124.1, 123.5, 123.0;

IR (KBr) ν_{max} 1078, 1043, 1034, 839, 754, 741, 721, 704, 681, 582, 540, 515, 484, 467, 449 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{37}H_{24}N$ [M]$^+$ 482.1903, found 482.1910.

6,7-Bis(4-methoxyphenyl)benzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate (94b).



6-(Naphthalen-1-yl)phenanthridine (**70l**) (0.30 mmol, 91.6 mg) and 1,2-bis(4-methoxyphenyl)ethyne (**52h**) (0.30 mmol, 71.5 mg) were used. Column chromatography of the residue on silica gel provided 59.3 mg (31%) of the title compound as a orange solid. Precipitation provided 20.0 mg (11%) of the title compound as an orange powder.

M.p. 170-180 °C;

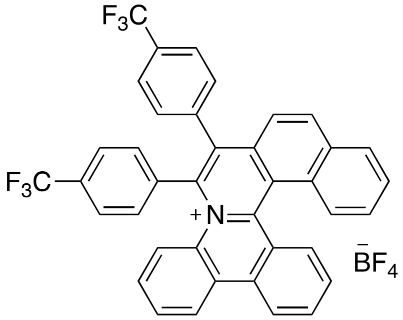
^{1}H NMR (600 MHz, $CDCl_3$) δ 8.60 (d, *J* = 8.0 Hz, 1H), 8.55 (d, *J* = 8.6 Hz, 2H), 8.34 (d, *J* = 8.4 Hz, 1H), 8.27 (d, *J* = 8.9 Hz, 1H), 8.05 (d, *J* = 8.1 Hz, 1H), 8.01 (t, *J* = 7.4 Hz, 1H), 7.81 (d, *J* = 8.1 Hz, 1H), 7.78–7.72 (m, 2H), 7.68–7.65 (m, 2H), 7.55 (t, *J* = 7.6 Hz, 1H), 7.48 (t, *J* = 7.6 Hz, 1H), 7.44 (d, *J* = 8.4 Hz, 1H), 7.30 (t, *J* = 7.9 Hz, 1H), 7.17 (d, *J* = 7.3 Hz, 1H), 6.76 (d, *J* = 7.9 Hz, 1H), 6.72 (d, *J* = 7.8 Hz, 1H), 6.66 (d, *J* = 7.9 Hz, 1H), 6.60 (d, *J* = 8.4 Hz, 2H), 3.85 (s, 3H), 3.74 (s, 3H);

^{13}C NMR (150 MHz, $CDCl_3$) δ 160.6, 159.9, 152.7, 146.4, 139.5, 138.4, 136.6, 135.6, 134.4, 134.2, 133.59, 133.56, 132.54, 132.4, 131.3, 130.4, 130.3, 130.2, 129.5, 129.3, 128.9, 128.8, 128.6, 127.7, 127.6, 126.4, 125.8, 125.7, 124.5, 124.0, 123.2, 123.1, 114.8, 114.6, 114.4, 114.1, 55.53, 55.51;

IR (KBr) ν_{max} 1606, 1514, 1248, 1178, 1051, 1024, 835, 760, 746, 552, 521 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{39}H_{28}NO_2$ [M]$^+$ 542.2115, found 542. 2118.

6,7-bis(4-(trifluoromethyl)phenyl)benzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate (94c).



6-(Naphthalen-1-yl)phenanthridine (**70l**) (0.30 mmol, 91.6 mg) and 1,2-bis(4-(trifluoromethyl)phenyl)ethyne (**52i**) (0.30 mmol, 94.3 mg) were used. Column chromatography of the residue on silica gel provided 45.3 mg (21%) of the title compound as a yellow-green solid. Precipitation was not successful.

M.p. 170-180 °C;

^{1}H NMR (400 MHz, CDCl$_3$) δ 8.59 (d, *J* = 8.5 Hz, 1H), 8.55 (d, *J* = 8.1 Hz, 1H), 8.51 (dd, *J* = 8.2, 1.0 Hz, 1H), 8.43 (d, *J* = 8.4 Hz, 1H), 8.32–8.25 (m, 2H), 8.04 (d, *J* = 7.7 Hz, 1H), 8.01–7.93 (m, 2H), 7.88 (dd, *J* = 7.9, 0.8 Hz, 1H), 7.78 (d, *J* = 8.7 Hz, 1H), 7.74 (ddd, *J* = 7.9, 7.1, 0.8 Hz, 1H), 7.65 (t, *J* = 7.5 Hz, 1H), 7.58–7.45 (m, 4H), 7.40 (dd, *J* = 8.1, 1.0 Hz, 1H), 7.32–7.24 (m, 2H), 6.98 (d, *J* = 7.6 Hz, 1H), 6.91 (d, *J* = 8.0 Hz, 1H);

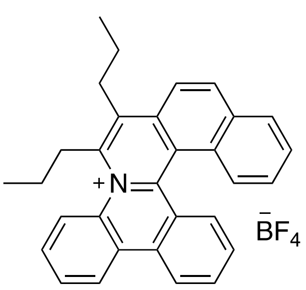
^{13}C NMR (101 MHz, CDCl$_3$) δ 154.0, 144.1, 138.7, 138.4, 138.3, 137.6, 135.7, 135.6, 133.69, 133.68, 133.59, 133.1, 133.0, 131.8, 131.4, 131.32, 131.29, 131.0, 130.6, 130.5, 130.4, 130.3, 129.7, 129.4, 129.3, 128.99, 128.97, 128.7, 127.7, 127.4, 125.8, 124.0, 123.60, 123.58, 122.6;

IR (powder) $\nu_{\max}$ 1709, 1618, 1607, 1582, 1423, 1408, 1359, 1321, 1112 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{39}H_{22}F_6N$ [M]$^+$ 618.1664, found 618.1660.

In ^{13}C NMR (101 MHz) spectra, quartets of carbon signals are not visible. ^{13}C NMR (150 MHz) could not be before the submission deadline for diploma thesis.

6,7-Dipropylbenzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate (94d).



6-(Naphthalen-1-yl)phenanthridine (**70l**) (0.30 mmol, 91.6 mg) and oct-4-yne (**52j**) (0.30 mmol, 44.0 µL) were used. Column chromatography of the residue on silica gel provided 103 mg (68%) of the title compound as a yellow solid. Precipitation provided 55.9 mg (37%) of the title compound as a dark yellow powder.

M.p. 123-124 °C;

^{1}H NMR (600 MHz, CDCl$_3$) δ 8.66 (d, *J* = 8.0 Hz, 1H), 8.60 (d, *J* = 7.9 Hz, 1H), 8.51 (d, *J* = 8.9 Hz, 1H), 8.47 (d, *J* = 8.5 Hz, 1H), 8.27 (d, *J* = 8.5 Hz, 1H), 8.21 (d, *J* = 9.1 Hz, 1H), 8.14 (d, *J* = 8.1 Hz, 1H), 8.09 (d, *J* = 8.0 Hz, 1H), 8.01 (t, *J* = 7.5 Hz, 1H), 7.96 (t, *J* = 7.4 Hz, 1H), 7.90 (t, *J* = 7.5 Hz, 1H), 7.73 (t, *J* = 7.6 Hz, 1H), 7.52 (t, *J* = 7.8 Hz, 1H), 7.45 (t, *J* = 7.6 Hz, 1H), 3.82–3.74 (m, 1H), 3.61–3.54 (m, 1H), 3.42–3.35 (m, 1H), 3.34–3.27 (m, 1H), 2.06–1.98 (m, 1H), 1.92–1.83 (m, 1H), 1.60–1.53 (m, 1H), 1.53–1.45 (m, 1H) 1.28 (t, *J* = 7.2 Hz, 3H), 0.74 (t, *J* = 7.3 Hz, 3H);

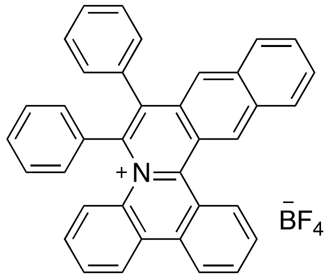
^{13}C NMR (101 MHz, $CDCl_3$) δ 153.3, 148.2, 139.2, 138.4, 135.6, 135.5, 133.33, 133.25, 131.6, 130.7, 130.2, 129.9, 129.8, 129.6, 129.51, 129.47, 128.7, 128.6, 128.0, 125.8, 125.5, 125.1, 124.0, 122.4, 120.8, 35.1, 31.5, 24.5, 24.0, 14.9, 13.9;

IR (KBr) ν_{max} 1576, 1419, 1406, 1047, 1030, 837, 768, 754, 723, 521 cm^{-1};

HRMS (ESI) *m*/*z* calculated for $C_{31}H_{28}N$ $[M]^+$ 414.2216, found 414.2219.

5.4.2. Synthesis of benzo[6,7]isoquinolino[2,1-*f*]phenanthridin-5-ium salts

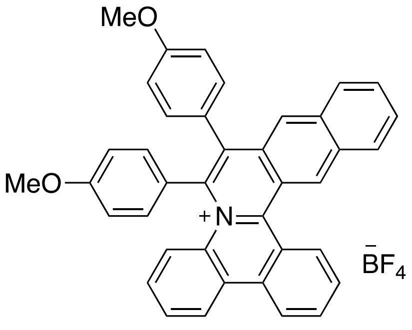
6,7-Diphenylbenzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate (95a).



6-(Naphthalen-2-yl)phenanthridine (**70m**) (0.30 mmol, 91.6 mg) and diphenylacetylene (**52a**) (0.30 mmol, 53.5 mg) were used. Column chromatography of the residue on silica gel provided 115 mg (67%) of the title compound as a dark red solid. Precipitation provided 58.3 mg (34%) of the title compound as a dark red powder; however, the compound was not of analytically pure. Other attempts to purify the title compound in order to obtain an analytically pure sample were not successful. Decomposition took place during column chromatography.

HRMS (ESI) *m*/*z* calculated for $C_{37}H_{24}N$ $[M]^+$ 482.1903, found 482.1904.

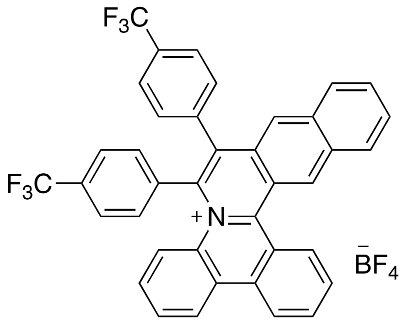
6,7-Bis(4-methoxyphenyl)benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate (95b).



6-(Naphthalen-2-yl)phenanthridine (**70m**) (0.30 mmol, 91.6 mg) and 1,2-bis(4-methoxyphenyl)ethyne (**52h**) (0.30 mmol, 71.5 mg) were used. Column chromatography of the residue on silica gel provided 143 mg (76%) of the title compound as a dark red solid. Precipitation provided 81.0 mg (43%) of the title compound as a dark red powder; however, the compound was not of analytically pure. Other attempts to purify the title compound in order to obtain an analytically pure sample were not successful. Decomposition took place during column chromatography.

HRMS (ESI) *m*/*z* calculated for $C_{39}H_{28}NO_2$ $[M]^+$ 542.2115, found 542.2114.

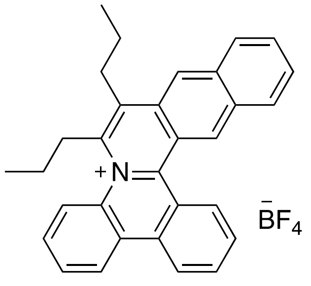
6,7-Bis(4-(trifluoromethyl)phenyl)benzo[6,7]isoquinolino[2,1-*f*]phenanthridine-5-ium tetrafluoroborate (95c).



6-(Naphthalen-2-yl)phenanthridine (**70m**) (0.30 mmol, 91.6 mg) and 1,2-bis(4- (trifluoromethyl)phenyl)ethyne (**52i**) (0.30 mmol, 94.3 mg) were used. Column chromatography of the residue on silica gel provided 101 mg (48%) of the title compound as a dark red solid; however, the compound was not of analytically pure. Other attempts to purify the title compound in order to obtain an analytically pure sample were not successful. Decomposition took place during column chromatography.

HRMS (ESI) *m*/*z* calculated for $C_{39}H_{22}F_6N$ $[M]^+$ 618.1664, found 618.1662.

6,7-Dipropylbenzo[6,7]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate (95d).

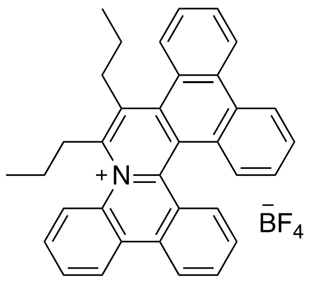


6-(Naphthalen-2-yl)phenanthridine (**70m**) (0.30 mmol, 91.6 mg) and oct-4-yne (**52j**) (0.30 mmol, 44.0 lL) were used. Column chromatography of the residue on silica gel provided 115 mg (76%) of the title compound as a red solid. Precipitation provided 55.8 mg (37%) of the title compound as a red powder; however, the compound was not of analytically pure. Other attempts to purify the title compound in order to obtain an analytically pure sample were not successful. Decomposition took place during column chromatography.

HRMS (ESI) *m*/*z* calculated for $C_{31}H_{28}N$ $[M]^+$ 414.2216, found 414.2217.

5.4.3. Synthesis of dibenzo[5,6:7,8]isoquinolino[2,1-*f*]phenanthridin-17-ium salt

18,19-Dipropyldibenzo[5,6:7,8]isoquinolino[2,1-f]phenanthridin-17-ium tetrafluoroborate (96b).

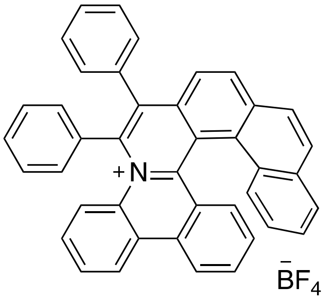


6-(Phenanthren-9-yl)phenanthridine (**70n**) (0.30 mmol, 107 mg) and oct-4-yne (**52j**) (0.30 mmol, 44.0 µL) were used. Column chromatography of the residue on silica provided 16.3 mg (10%) of the title compound as a yellow solid. Precipitation provided 12.8 mg (8%) of the title compound as a yellow powder.

HRMS (APCI) *m*/*z* calculated for $C_{35}H_{30}N$ $[M]^+$464.2373, found 464.2366.

5.4.4. Synthesis of naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts

6,7-Diphenylnaphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate (97a).



6-(Phenanthren-4-yl)phenanthridine (**70o**) (0.15 mmol, 53.3 mg), diphenylacetylene (**52a**) (0.15 mmol, 26.7 mg), [Cp*$RhCl_2$]$_2$ (15.0 µmol, 9.30 mg), $AgBF_4$ (0.15 mmol, 29.2 mg) and Cu(OAc)$_2$ (0.17 mmol, 30.9 mg) were dissolved in DCE (5 mL). Stirring reaction mixture was heated at 100 °C for 24 h. After cooling down to 25 °C, the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (DCM/MeOH, 100/1 → 20/1) provided 47.1 mg (51%) of the title compound as a orange-yellow solid. Precipitation from DCM solution with cyclohexane provided 24.0 mg (26%) of the title compound as a orange-yellow powder.

M.p. 160-170 °C;

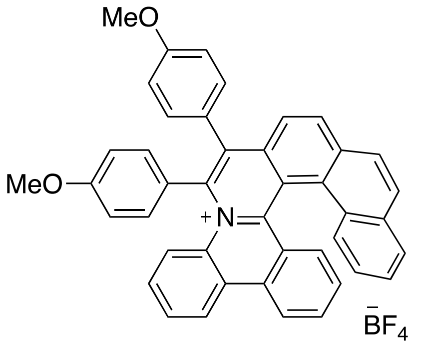
^{1}H NMR (400 MHz, $CDCl_3$) δ 8.55 (d, *J* = 7.5 Hz, 1H), 8.46 (d, *J* = 8.1 Hz, 1H), 8.34 (d, *J* = 8.8 Hz, 1H), 8.13 (d, *J* = 8.5 Hz, 1H), 8.03 (d, *J* = 7.7 Hz, 1H), 7.99 (d, *J* = 8.6 Hz, 1H), 7.92–7.87 (m, 2H), 7.81 (d, *J* = 8.7 Hz, 1H), 7.74–7.69 (m, 2H), 7.66 (t, *J* = 7.6 Hz, 1H), 7.61 (t, *J* = 7.7 Hz, 1H), 7.55 (d, *J* = 8.5 Hz, 1H), 7.37 (dd, *J* = 14.4, 7.3 Hz, 2H), 7.32 (t, *J* = 8.0 Hz, 1H), 7.28–7.22 (m, 3H), 7.14 (ddd, *J* = 7.7, 7.7, 0.9 Hz, 1H), 7.11–7.05 (m, 1H), 6.96 (dd, *J* = 15.9, 7.9 Hz, 2H), 6.71 (d, *J* = 7.7 Hz, 1H), 6.64 (d, *J* = 7.7 Hz, 1H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 154.6, 145.8, 138.6, 137.8, 136.3, 135.3, 134.38, 134.36, 133.8, 133.7, 133.2, 133.0, 132.6, 132.1, 131.1, 130.6, 129.9, 129.8, 129.7, 129.6, 129.3, 129.12, 129.06, 128.9, 128.72, 128.65, 128.61, 128.55, 128.54, 127.91, 127.87, 127.7, 127.6, 125.74, 125.72, 124.5, 124.1, 123.3, 119.7;

IR (powder) ν_{max} 1603, 1571, 1488, 1478, 1445, 1433, 1400, 1382, 1040 cm^{-1};

HRMS (APCI) *m*/*z* calculated for $C_{41}H_{26}N$ $[M]^+$ 532.2060, found 532.2057.

6,7-Bis(4-methoxyphenyl)naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate (97b).



6-(Phenanthren-4-yl)phenanthridine (**70o**) (0.15 mmol, 53.3 mg), 1,2-bis(4-methoxyphenyl)ethyne (**52h**) (0.15 mmol, 35.7 mg), $[Cp^*RhCl_2]_2$ (15.0 μmol, 9.30 mg), $AgBF_4$ (0.15 mmol, 29.2 mg) and $Cu(OAc)_2$ (0.17 mmol, 30.9 mg) were dissolved in DCE (5 mL). Stirring reaction mixture was heated at 100 °C for 24 h. After cooling down to 25 °C, the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (DCM/MeOH, 100/1 → 20/1) provided 31.5 mg (31%) of the title compound as a red-orange solid. Precipitation from DCM solution with cyclohexane provided 19.5 mg (19%) of the title compound as a red-orange powder.

M.p. 150-160 °C;

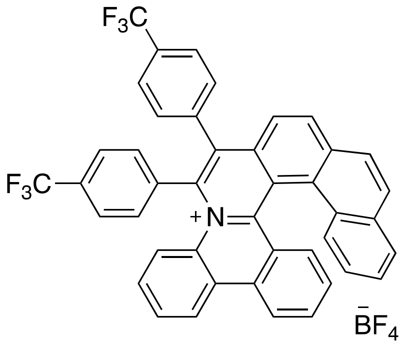
^{1}H NMR (400 MHz, $CDCl_3$) δ 8.55 (d, J = 8.2 Hz, 1H), 8.45 (d, J = 8.2 Hz, 1H), 8.34 (d, J = 9.0 Hz, 1H), 8.14 (d, J = 8.4 Hz, 1H), 8.00 (d, J = 8.4 Hz, 1H), 7.90 (d, J = 9.3 Hz, 2H), 7.85 (d, J = 8.2 Hz, 2H), 7.73 (t, J = 7.5 Hz, 1H), 7.66 (t, J = 7.6 Hz, 1H), 7.56 (d, J = 8.6 Hz, 1H), 7.50 (d, J = 8.6 Hz, 1H), 7.37 (t, J = 7.5 Hz, 2H), 7.20 (d, J = 8.5 Hz, 1H), 7.16 (dd, J = 8.4, 2.6 Hz, 1H), 7.00–6.92 (m, 2H), 6.81 (d, J = 7.7 Hz, 1H), 6.72 (dd, J = 8.4, 2.6 Hz, 1H), 6.68–6.60 (m, 2H), 6.58 (dd, J = 8.5, 1.9 Hz, 1H), 3.86 (s, 3H), 3.76 (s, 3H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 160.5, 159.8, 154.2, 146.2, 139.2, 137.9, 136.2, 134.4, 134.3, 134.0, 133.70, 133.68, 133.2, 132.3, 132.1, 131.3, 130.9, 129.60, 129.55, 129.2, 129.0, 128.72, 128.69, 128.4, 128.3, 128.0, 127.9, 127.7, 127.6, 126.9, 126.3, 125.8, 125.7, 124.6, 124.4, 123.4, 119.5, 114.7, 114.6, 114.4, 114.1, 55.5;

IR (powder) ν_{max} 1608, 1515, 1478, 1401, 1293, 1253, 1180, 1057, 1031 cm^{-1};

HRMS (APCI) m/z calculated for $C_{43}H_{30}NO_2$ $[M]^+$ 592.2271, found 592.2265.

6,7-Bis(4-(trifluoromethyl)phenyl)naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate (97c).



6-(Phenanthren-4-yl)phenanthridine (**70o**) (56.0 μmol, 20.0 mg), 1,2-bis(4-methoxyphenyl)ethyne (**52h**) (56.0 μmol, 17.7 mg), $[Cp^*RhCl_2]_2$ (5.60 μmol, 3.50 mg), $AgBF_4$ (56.0 μmol, 11.0 mg) and $Cu(OAc)_2$ (62.0 μmol, 11.6 mg) were dissolved in DCE (3 mL). Stirring reaction mixture was heated at 100 °C for 24 h. After cooling down to 25 °C, the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (DCM/MeOH, 100/1 → 20/1) provided 8.7 mg (21%) of the title compound as a yellow-orange solid. Precipitation from DCM solution with cyclohexane provided 7.3 mg (17%) of the title compound as a orange-yellow powder.

M.p. 250-260 °C;

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.49 (dd, J = 8.1, 0.8 Hz, 1H), 8.39 (d, J = 8.0 Hz, 1H), 8.36 (d, J = 8.3 Hz, 1H), 8.33 (d, J = 8.7 Hz, 1H), 8.11 (d, J = 8.6 Hz, 1H), 8.03 (d, J = 7.7 Hz, 1H), 7.96 (d, J = 8.7 Hz, 1H), 7.93 (d, J = 9.1 Hz, 1H), 7.89–7.84 (m, 2H), 7.70 (t, J = 7.6 Hz, 1H), 7.67–7.60 (m, 3H), 7.51 (d, J = 7.6 Hz, 1H), 7.40 (d, J = 7.9 Hz, 1H), 7.39–7.27 (m, 4H), 7.01–6.91 (m, 2H), 6.90 (d, J = 8.2 Hz, 1H), 6.82 (d, J = 8.0 Hz, 1H);

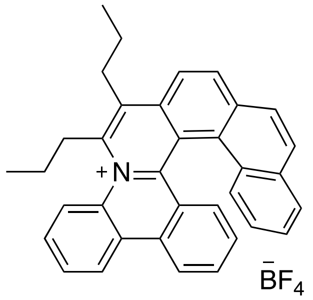
^{13}C NMR (101 MHz, $CDCl_3$) δ 155.3, 143.9, 138.6, 138.1, 138.0, 137.9, 135.1, 134.3, 133.9, 133.7, 133.49, 133.45, 133.2, 132.1, 131.5, 131.0, 130.4, 129.8, 129.74, 129.69, 129.1, 128.9, 128.8, 128.7, 128.5, 128.2, 128.0, 127.9, 127.8, 125.99, 125.95, 125.8, 125.6, 125.46, 125.42, 124.0, 123.8, 123.0, 120.1;

IR (powder) ν_{max} 1618, 1608, 1574, 1403, 1380, 1324, 1166, 1112, 1076, 1064 cm^{-1};

HRMS (APCI) m/z calculated for $C_{43}H_{24}F_6N$ $[M]^+$ 668.1807, found 668.1800.

In ^{13}C NMR (101 MHz) spectra, quartets of carbon signals are not visible. ^{13}C NMR (150 MHz) could not be before the submission deadline for diploma thesis.

6,7-Dipropylnaphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium tetrafluoroborate (97d).



6-(Phenanthren-4-yl)phenanthridine (**70o**) (0.11 mmol, 40.0 mg), oct-4-yne (**52j**) (0.11 mmol, 16.0 µL), $[Cp^*RhCl_2]_2$ (11.0 µmol, 6.80 mg), $AgBF_4$ (0.11 mmol, 21.4 mg) and $Cu(OAc)_2$ (0.12 mmol, 22.7 mg) were dissolved in DCE (5 mL). Stirring reaction mixture was heated at 100 °C for 24 h. After cooling down to 25 °C, the reaction mixture was filtered through a pad of Celite and washed with DCM (200 mL). Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (DCM/MeOH, 100/1 → 20/1) provided 12.1 mg (20%) of the title compound as a yellow-orange solid. Precipitation from DCM solution with cyclohexane provided 10.8 mg (18%) of the title compound as a orange-yellow powder.

M.p. 100-110 °C;

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.64 (dd, *J* = 7.8, 1.6 Hz, 1H), 8.58 (d, *J* = 8.9 Hz, 1H), 8.42 (d, *J* = 8.0 Hz, 1H), 8.39 (dd, *J* = 8.2, 0.8 Hz, 1H), 8.36 (d, *J* = 8.9 Hz, 1H), 8.13 (d, *J* = 8.5 Hz, 1H), 8.05 (d, *J* = 8.5 Hz, 1H), 8.02–7.95 (m, 2H), 7.88 (d, *J* = 7.8 Hz, 1H), 7.61 (ddd, *J* = 8.2, 7.3, 1.0 Hz, 1H), 7.35 (ddd, *J* = 7.9, 7.1, 0.9 Hz, 1H), 7.21 (d, *J* = 8.6 Hz, 1H), 7.07 (dd, *J* = 8.4, 0.6 Hz, 1H), 6.93–6.86 (m, 2H), 3.86–3.75 (m, 1H), 3.63–3.53 (m, 1H), 3.48–3.29 (m, 2H), 2.06–1.81 (m, 2H), 1.70–1.58 (m, 2H), 1.28 (t, *J* = 7.2 Hz, 3H), 0.83 (t, *J* = 7.3 Hz, 3H);

^{13}C NMR (101 MHz, $CDCl_3$) δ 155.1, 148.4, 138.3, 137.9, 134.8, 134.3, 133.8, 132.97, 132.95, 132.0, 130.8, 130.4, 129.8, 129.2, 128.8, 128.7, 128.3, 128.2, 128.1, 127.8, 127.4, 125.9, 125.8, 125.6, 125.0, 123.3, 122.0, 118.6, 35.0, 31.6, 24.5, 23.8, 14.9, 14.0;

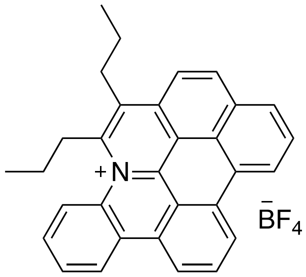
IR (powder) ν_{max} 1605, 1536, 1463, 1431, 1399, 1384, 1254, 1150, 1060 cm^{-1};

HRMS (APCI) *m*/*z* calculated for $C_{35}H_{30}N$ $[M]^+$464.2373, found 464.2367.

5.5. Scholl reaction

14,15-Dipropylnaphtho[2',1',8':4,5,6]quinolino[1,8,7-fgh]phenanthridin-13-ium tetrafluoroborate (98).

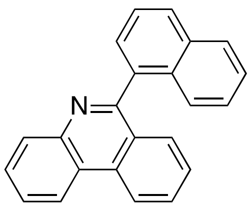
6,7-Dipropylbenzo[7,8]isoquinolino[2,1-*f*]phenanthridin-5-ium tetrafluoroborate (**94d**) (20.0 μmol, 10 mg) and DDQ (0.16 mmol, 36.5 mg) were dissolved in anhydrous DCM (10.5 mL) under argon atmosphere. The resulting stirring solution was cooled down to 0 °C. Trifluoroacetic acid (6.30 mmol, 0.55 mL) was added dropwise and the reaction was left stirring at 0 °C for 30 min. Then, Et_3N (1.20) was added. The reaction mixture was washed with distilled water (3×10 mL) and dried over anhydrous Na_2SO_4. Volatiles were removed under reduced pressure. Column chromatography of the residue on silica gel (DCM/MeOH, 100/1 → 20/1) provided 0.71 mg (7%) of the title compound as a yellow solid.



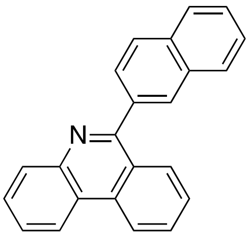
HRMS (ESI) *m*/*z* calculated for $C_{31}H_{26}N$ $[M]^+$ 412.2060, found 412.2053.

6. Conclusion

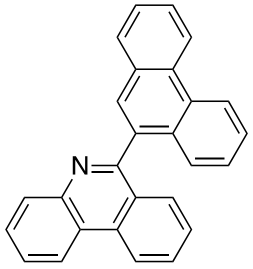
1. Synthesis of phenanthridine **70m** using catalytic C–C bond cleavage/annulation sequence was successful. Unfortunately, this reaction was not effective with sterically hindered nitrile group. Therefore the synthesis of phenanthridines **70l**, **70n** and **70o** was done using Suzuki-Miyaura cross-coupling reaction.



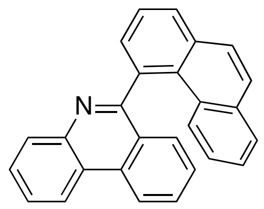
70l



70m

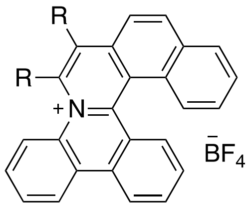


70n

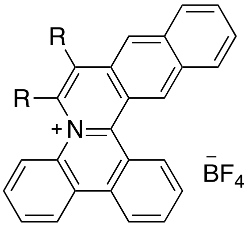


70o

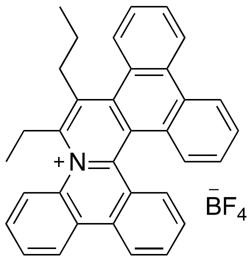
2. By catalytic C–H bond activation/annulation sequence, four sets of cationic helical *N*-heterocycles were prepared. By C–H bond activation in phenanthridine **70l**, benzo[7,8]isoquinolino[2,1-f]phenanthridine-5-ium salts **94** with the [5]helical scaffold were prepared in mediocre yields. By C–H bond activation in phenanthridine **70m**, benzo[6,7]isoquinolino[2,1-f]phenanthridine-5-ium salts **95** with the [4]helical scaffold were synthesized in higher yields, but were unstable and underwent decomposition. Phenanthridine **70n** was not suitable substrate for catalytic C–H bond activation/annulation sequence. The C–H bond annulation step did not proceed with sterically demanding diphenylethyne (**52a**), but with sterically less demanding oct-4-yne (**52j**) the product 18,19-dipropyldibenzo[5,6:7,8]isoquinolino[2,1-f]phenanthridin-17-ium tetrafluoroborate (**96b**) with the [5]helical scaffold was formed in lower yield. Last phenanthridine **70o** provided by C–H bond activation/annulation naphtho[2',1':7,8]isoquinolino[2,1-f]phenanthridin-5-ium salts **97** with the [6]helical scaffold in good yields.



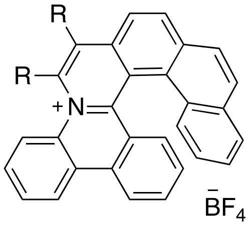
94



95



96b



97

3. Absorption and emission spectra of compounds **94** and **97** were recorded and structure of phenanthridines **70m** and **70n** was confirmed by single crystal X-ray diffraction analysis. The structure of compound **94a** was also confirmed by single crystal X-ray diffraction analysis.

4. In addition, Scholl reaction of compound **96b** was successfully performed and can be used in further research projects of prepared cationic helical *N*-heterocycles.

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