SYNTHESIS AND APPLICATION OF DIAZA[5]HELICENES

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Abstract. *m,n-Diaza[5]helicenes are a distinct group of compounds that constitutes a borderline between smaller, planar diazaaromatic compounds and larger, configurationally stable m,n-diaza[≥6]helicenes. Although m,n-diaza[5]helicenes are not configurationally stable under ambient conditions, they represent ideal model targets for the development of new synthetic methods toward the larger azahelicenes. Their preparation has been based on various synthetic strategies encompassing photochemical reactions, catalytic cyclotrimerizations, cross-coupling methodologies, condensation reactions, etc. as the key synthetic steps. As far as their properties are concerned, they possess basic character thanks to the presence of two nitrogen atoms, and some of the synthesized representatives were tested as candidates in material science.*

Contents

1. Introduction

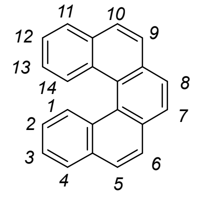
The chemical community has seen significant progress in the synthesis of inherently chiral aromatics with a helical scaffold in recent decades. Various helical substances are nowadays accessible thanks to diverse synthetic strategies. Incorporation of heteroatoms into the helical framework constitutes not only an option to change chemical, physical, and structural properties of helical compounds but also a method for synthesizing even extensive libraries of diverse compounds possessing a helical scaffold.[1,2,3,4,5,6,7,8,9]

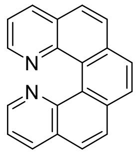
This review selectively focuses on synthetic methods towards *m,n*-diaza[5]helicenes, because they represent a class of compounds that stand in between planar heteroaromatic compounds consisting of three or four aromatic and heteroaromatic rings and configurationally stable longer or larger heteroatom embedded [n]helicenes (n≥6).

2. Symmetric *m,n*-diaza[5]helicenes

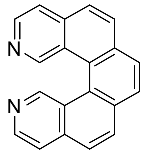
2.1. List of symmetric *m,n*-diaza[5]helicenes

There are seven symmetric regioisomeric *m,n*-diaza[5]helicenes (Figure 1).

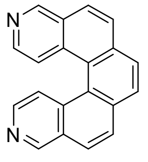




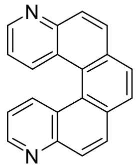
benzo[1,2-*h*:4,3-*h'*]diquinoline
1,14-diaza[5]helicene, **1**



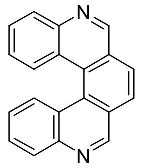
benzo[1,2-*h*:4,3-*h'*]diisoquinoline
2,13-diaza[5]helicene, **2**



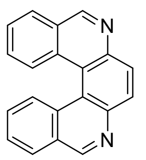
benzo[2,1-*f*:3,4-*f'*]diisoquinoline
3,12-diaza[5]helicene, **3**



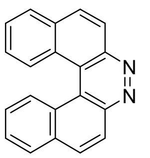
benzo[2,1-*f*:3,4-*f'*]diquinoline
4,11-diaza[5]helicene, **4**



dibenzo[*a*,*k*][3,8]phenanthroline
5,10-diaza[5]helicene, **5**



dibenzo[*a*,*k*][4,7]phenanthroline
6,9-diaza[5]helicene, **6**



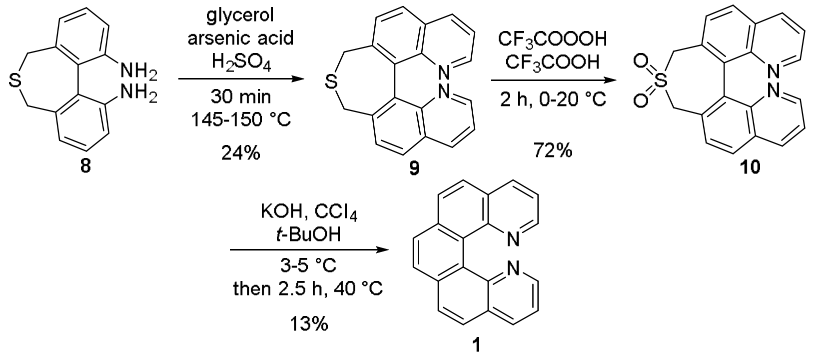
benzo[*f*]naphtho[2,1-*c*]cinnoline
7,8-diaza[5]helicene, **7**

Figure 1. A list of symmetric *m,n*-diaza[5]helicenes.

2.2. 1,14-Diaza[5]helicenes (benzo[1,2-*h*:4,3-*h'*]diquinolines)

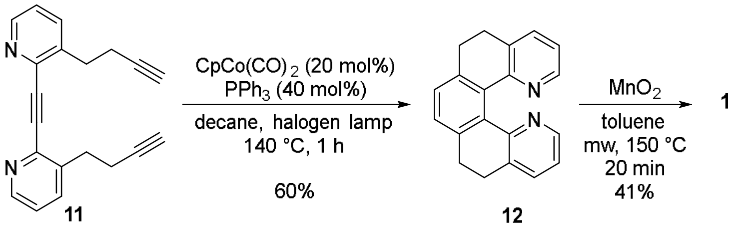
2.2.1. Synthesis

The first synthesis of 1,14-diaza[5]helicene **1** was reported by Staab *et al.* in 1989 (Scheme 1).[10] The synthetic route started with conversion of 5,7-dihydrodibenzo[*c,e*]-thiepin-1,11-diamine **8** *via* double Skraup reaction to 7,9-dihydrothiepino[3,4-*h*:6,5-*h'*]diquinoline **9** (24% yield). The subsequent oxidation with trifluoroperoxyacetic acid in trifluoroacetic acid furnished sulfone **10** in 72% yield. Its treatment with KOH and CCl_4 in *t*-BuOH induced Ramberg-Bäcklund rearrangement giving rise to **1** in 13% yield.

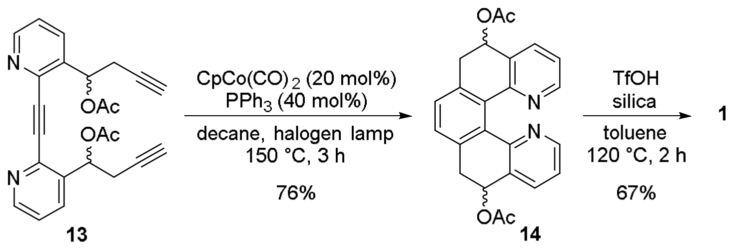


Scheme 1. The first synthesis of **1**.

It took almost 20 years to develop a new synthetic approach to **1**, and the second synthesis was reported by Starý *et al.* in 2008. It was based on a catalytic intramolecular cyclotrimerization of triyne **11** with $CpCo(CO)_2$ (Vollhardt's catalyst) yielding 5,6,9,10-tetrahydrobenzo[1,2-*h*:4,3-*h'*]diquinoline **12** in 60% yield (Scheme 2).[11] Finally, its aromatization using MnO_2 provided **1** in 41% yield. The cyclotrimerization approach was also extended to a reaction of triyne **13** that yielded 5,6,9,10-tetrahydrobenzo[1,2-*h*:4,3-*h'*]diquinoline-5,10-diyl diacetate **14** in 76% yield. Its subsequent treatment with TfOH on silica gel at 120 °C induced a two-fold elimination furnishing **1** in 67% yield (Scheme 3).[12]

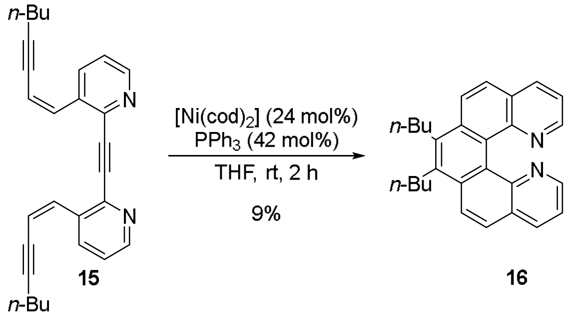


Scheme 2. Synthesis of **1** *via* catalytic cyclotrimerization of **11**.



Scheme 3. Synthesis of **1** *via* catalytic cyclotrimerization of **13**.

A similar cyclotrimerization approach was also applied to the synthesis of 7,8-dibutyl-5,10-diaza[5]helicene **16**, which was reported by Starý *et al.* in 2009.[13] Their strategy utilized intramolecular cyclotrimerization of 2,2′-ethynediylbis(3-((1*Z*)-oct-1-en-3-yn-1-yl)pyridine) **15** catalyzed by a combination of $Ni(cod)_2$ in conjunction with 2 equiv of PPh_3 (Scheme 4). However, the desired compound **16** was obtained in only 9% yield, due to the prevailing polymerization of the pyridine-derived triyne.



Scheme 4. Synthesis of **16** *via* catalytic cyclotrimerization of **15.**

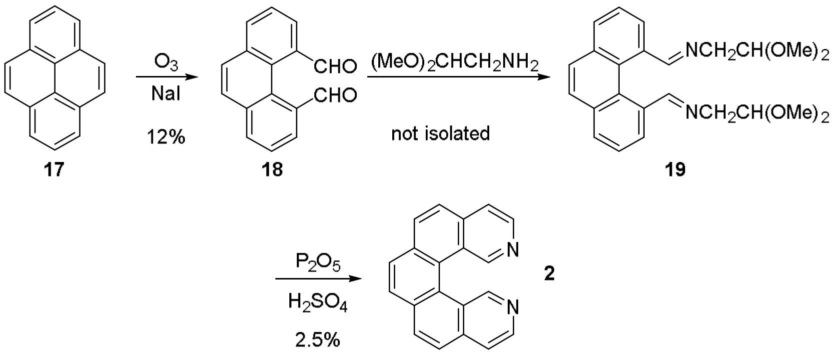
2.2.2. Properties and application.

Acid-base dissociation constants pK_a of **1** determined by capillary zone electrophoresis were calculated to be 7.56±0.38 ($pK_{a,1}$) and 8.85±0.26 ($pK_{a,2}$) in methanol. For water solutions, these values were calculated as 7.12±0.58 ($pK_{a,1}$) and 8.39±0.46 ($pK_{a,2}$).[14] The same authors reported an extended study later.[15] A comprehensive study on the physicochemical properties (inversion barriers, protonation constants and redox potentials) of **1** was reported.[16] Single crystal X-ray diffraction data for **1** were reported[10] and these data were also mentioned in a report dealing with structural properties of other aza- and diazahelical compounds.[17]

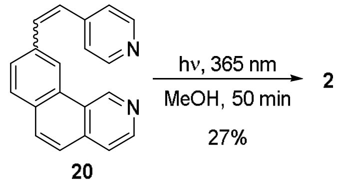
2.3. 2,13-Diaza[5]helicenes (benzo[1,2-*h*:4,3-*h′*]diisoquinolines)

2.3.1. Synthesis

The first synthesis of 2,13-diaza[5]helicene **2** was reported by Caronna *et al.* in 2002 and was based on the transformation of pyrene **17**. The synthetic route started with ozonolysis of pyrene **17**, which gave rise to dialdehyde **18** in 12% yield. Its reaction with aminoacetaldehyde dimethylacetal formed diimine **19**, which was subjected to cyclization under acidic conditions without further purification. After workup, 2,13-diaza[5]helicene **2** was isolated in a low yield of 2.5% (Scheme 5).[18] Because of the low yield, Caronna *et al.* developed a photochemical procedure for the synthesis of **2** in 2009.[19] In this case, the photochemical cyclization of 9-[2-pyridin-4-yl-vinyl]-benzo[*h*]isoquinoline **20** under irradiation at 365 nm in MeOH was the crucial step, and compound **2** was obtained in 27% yield (Scheme 6).



Scheme 5. Synthesis of **2** from pyrene **17**.



Scheme 6. Photochemical approach to **2**.

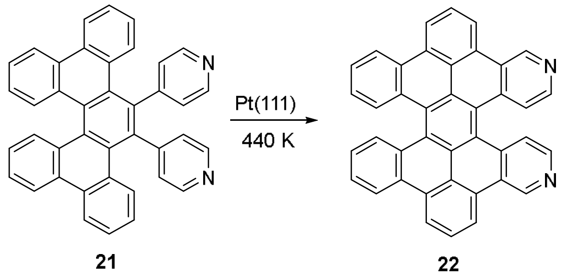
2.3.2. Properties and application

An acid-base dissociation constant pK_a of **2** determined by capillary zone electrophoresis was calculated to be 6.20±0.04 in methanol.[15] A comprehensive study on the physicochemical properties (inversion barriers, protonation constants and redox potentials) of **2** was reported.[16] Compound **2** has fluorescence emission maxima at 443 and 472 nm (quantum yields and other details were not provided).[18] Prolonged irradiation (365 nm) of the hexane solution of **2** leads to the formation of 7,8-diaza-benzo[*ghi*]perylene, which was isolated in 77% yield.[19]

2.4. 3,12-Diaza[5]helicenes (benzo[2,1-*f*:3,4-*f'*]diisoquinolines)

2.4.1. Synthesis

A synthesis of 3,12-diaza[5]helicene **3** has not been reported yet. However, its derivatives with expanded π-conjugated systems were described by Martin-Gabo *et al.* in 2014. Among them belongs nanohelicene **22** possessing an enlarged π-conjugated system. It was prepared through on-surface chemistry (Scheme 7).[20] The nonplanar 17,18-di(pyridin-4-yl)dibenzo[*f,j*]picene **21** was deposited on Pt(111) surface, heated to 440 K resulting in two-fold cyclodehydrogenation that gave rise to the *N*-doped nanohelicene **22**.



Scheme 7. Cyclodehydrogenation of **21** to **22**.

It is also worth mentioning that a natural compound possessing the 3,12-diaza[5]helicene framework, purpurfusarin **23**, was isolated from the filamentous fungus *Fusarium graminearum* (Figure 2).[21]

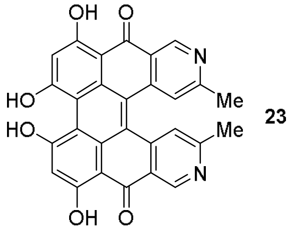
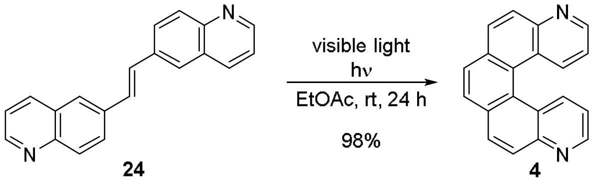


Figure 2. Purpurfusarin **23**.

2.5. 4,11-Diaza[5]helicenes (benzo[2,1-*f*:3,4-*f'*]diquinolines)

2.5.1. Synthesis

4,11-Diaza[5]helicene **4** was synthesized *via* a photochemical pathway, based on irradiation of (*E*)-1,2-di(quinolin-6-yl)ethene **24** with visible light at room temperature for 24 h as reported by Caronna *et al.* in 2005 (Scheme 8).[22] Thus, **4** was obtained in 98% isolated yield.



Scheme 8. Photochemical synthesis of 4,11-diaza[5]helicene **4** from **24**.

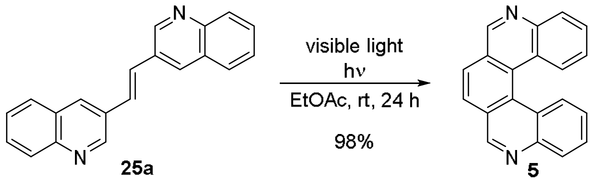
2.5.2. Properties and application

A calculated molecular electrostatic potential (MEP) of **4** was reported. It clearly shows negative values of the electrostatic potential around the pyridinic/quinolinic nitrogen atoms.[23] No further information on properties and/or applications is available.

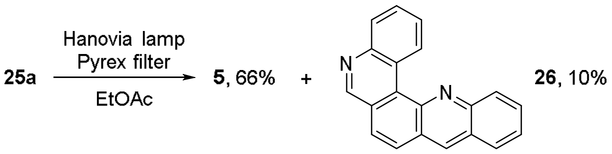
2.6. 5,10-Diaza[5]helicenes (dibenzo[*a*,*k*][3,8]phenanthrolines)

2.6.1. Synthesis

5,10-Diaza[5]helicene **5** was originally synthesized by using the same procedure as for **4**, by Caronna *et al.* in 2005. The procedure was based on irradiation of (*E*)-1,2-di(quinolin-3-yl)ethene **25a** with visible light at room temperature for 24 h (Scheme 9).[22] The reaction proceeded almost quantitatively and **5** was obtained in 98% isolated yield. The same procedure was used again by Caronna[24] and Clennan.[25,26] Similar photochemical reaction conditions were applied for the preparation of **5** by Clennan *et al.* Irradiation of alkene **25a** with a medium pressure Hanovia lamp through a Pyrex filter gave **5** in 66% yield along with a 10% yield of benzo[*b*]1,8-diaza[4]helicene **26** (Scheme 10).[26,27]

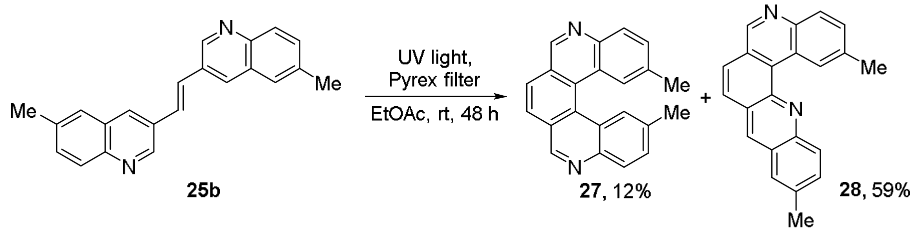


Scheme 9. Synthesis of 5,10-diaza[5]helicene **5** from **25a** by using visible light irradiation.



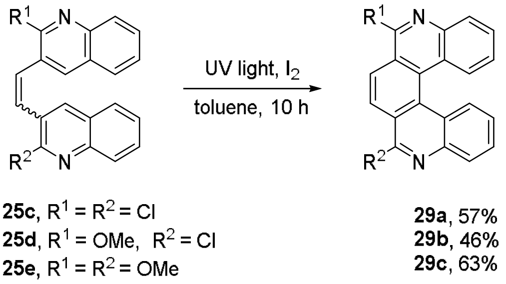
Scheme 10. Synthesis of 5,10-diaza[5]helicene **5** from **25a** by using Hanovia lamp irradiation.

Interestingly, the ratio of [5]helicene *vs.* [4]helicene was reversed in the case of a dimethylated alkene. Thus irradiation of (*E*)-1,2-bis(6-methylquinolin-3-yl)ethene **25b** gave rise to a mixture of 9,12-dimethyldibenzo[*a*,*k*][3,8]phenanthroline **27** and 2,11-dimethyldibenzo[*b*,*k*][1,8]phenanthroline **28** in 12% and 59% yields, respectively (Scheme 11).[28] In a similar manner, **5** was synthesized by irradiation of **25a** in an RPR-100 photoreactor in 73% yield.[29]

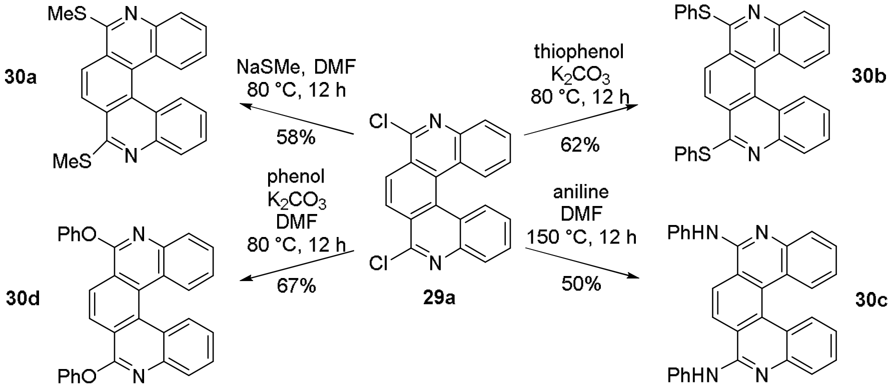


Scheme 11. Synthesis of 9,12-dimethyldibenzo[*a*,*k*][3,8]phenanthroline **27**.

Photochemical cyclization of **25c-25e** was also the basis for syntheses of three variously 6,9-disubstituted 5,10-diaza[5]helicenes **29a-29c**, as it was reported by Dehaen *et al.* in 2012 (Scheme 12).[30] 6,9-Dichloro-5,10-diaza[5]helicene **29a** was converted, *via* nucleophilic aromatic substitution with thiophenol, aniline, phenol, and sodium methylthiolate, to a series of symmetric 6,9-disubstituted 5,10-diaza[5]helicene **30a-30d** (Scheme 13). Diaza[5]helicene **30c** was also prepared by Buchwald-Hartwig coupling of **29a** with aniline in 57% yield, which was higher than the yield obtained by the above-mentioned nucleophilic aromatic substitution. Suzuki-Miyaura cross-coupling of **29a** with *p*-tolylboronic acid gave rise to 6,9-ditolyl-5,10-diaza[5]helicene **30e** in 42% yield (Scheme 14). In a similar manner, a reaction of **29a** with (*S*)-phenylethylamine under Buchwald-Hartwig coupling conditions yielded *P,S,S*-**30f** and *M,S,S*-**30f** as 1:1 diastereomeric mixture (Scheme 15).

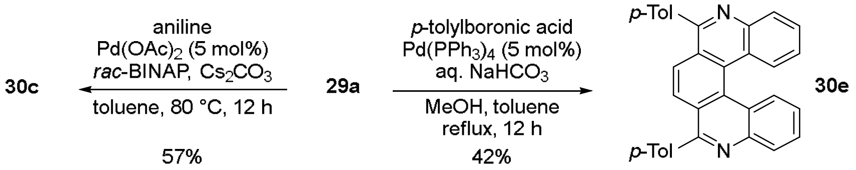


Scheme 12. Synthesis of **29** *via* photochemical cyclization.

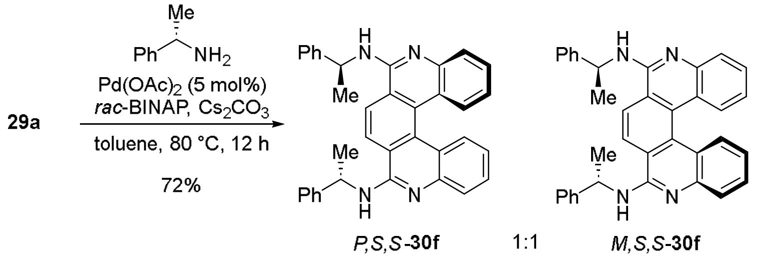


Scheme 13. Conversion of **29a** to **30a-30d** *via* nucleophilic aromatic substitution.

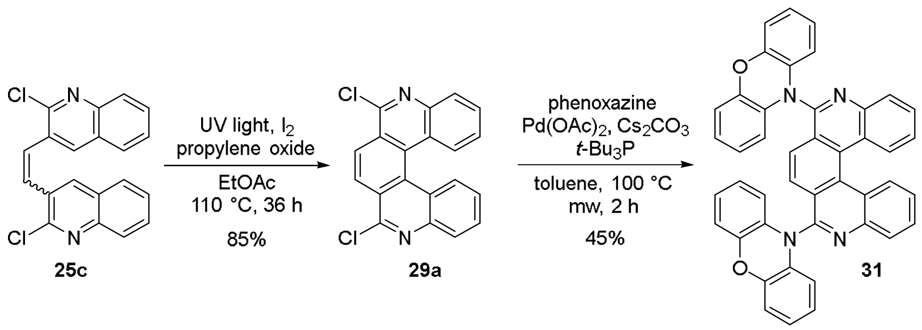
A slightly modified photochemical approach to **29a** was exploited by Dias *et al.* in 2018 (Scheme 16). After the formation of **29a**, they used Buchwald-Hartwig coupling with phenoxazine to prepare **31**.[31]



Scheme 14. Suzuki-Miyaura cross-coupling to **30e** and Buchwald-Hartwig coupling to **30c.**

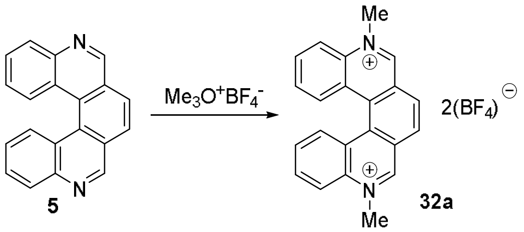


Scheme 15. Suzuki-Miyaura cross-coupling of with **29a** (*S*)-phenylethylamine to chiral **30f**.



Scheme 16. Synthesis of **26** *via* Buchwald-Hartwig coupling.

Double quaternization of **5** to *N,N'*-dimethyl-5,10-diaza[5]helicene **32a** was achieved by using trimethyloxonium tetrafluoroborate (Scheme 17).[25,26] *N,N*-dimethylaza[5]helicene dicyanoaurate **32b** (not shown) was prepared by conversion of bistetrafluoroborate **32a** (or dichloride that shows high solubility in aqueous solvents) by using potassium dicyanoaurate.[29]



Scheme 17. Conversion of **5** to *N,N'*-dimethyl-5,10-diaza[5]helicene **32a**.

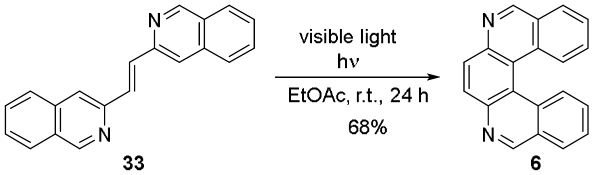
2.6.2. Properties and application

Proton affinities and electron distribution were calculated by using quantum-mechanical density functional for **5**.[24] Photochemical and electrochemical properties of diazonium salt **32a** were determined. Its electrostatic potential energy surface and racemization barrier were calculated as well. In addition, single crystal X-ray analysis of **32a** was carried out.[25,26] Quenching of **32a** with sulfides was studied.[27] Applications of **5** and **32a** in the fields of optoelectronic, semiconducting and photovoltaic devices with respect to advanced quantum chemical approaches have been described.[32] Compound **5** has fluorescence emission maxima at 412 and 438 nm (quantum yields and other details were not provided).[18]

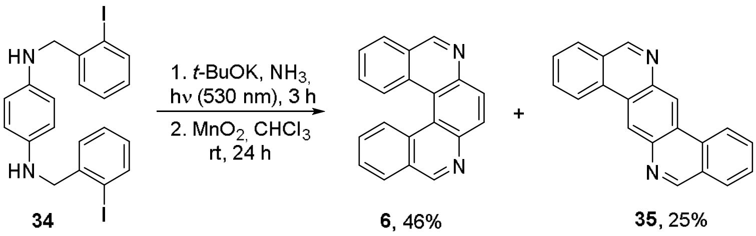
2.7. 6,9-Diaza[5]helicenes (dibenzo[*a,k*][4,7]phenanthrolines)

2.7.1. Synthesis

There are just two reports describing syntheses of 6,9-diaza[5]helicene **6**. The first report was done by Caronna *et al.* who utilized a photochemical approach analogical to syntheses of **4** and **5**. Irradiation of the EtOAc solution of (*E*)-1,2-di(isoquinolin-3-yl)ethene **33** with visible light at room temperature for 24 h provided **6** in 68% yield (Scheme 18).[22] The second approach was reported by Budén *et al.* in 2015 and was based on a photostimulated cyclization of N^1,N^4-bis(2-iodobenzyl)benzene-1,4-diamine **34** in the presence of an excess of *t*-BuOK under nitrogen atmosphere (Scheme 19).[33] The course of the reaction is rather complicated and it was suggested to proceed *via* intramolecular $S_{RN}1$ reaction. The crude product was immediately oxidized with MnO_2 to **6**. In addition to **6** (46%), isoquinolino[3,4-*b*]phenanthridine **35** was also isolated (25%) as a side-product.



Scheme 18. Photochemical synthesis of 6,9-diaza[5]helicene **6** from **33**.



Scheme 19. Formation of **6** from **34**.

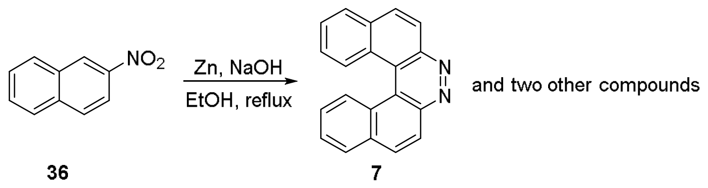
2.7.1. Properties and application

The fluorescence emission maxima of **6** are at 424 and 438 nm. Quantum yields and other details were not provided.[18]

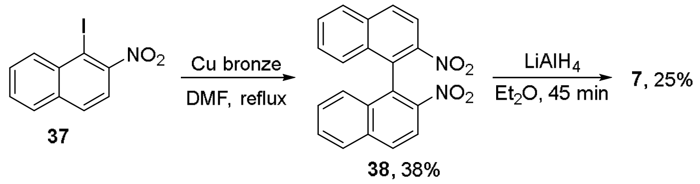
2.8. 7,8-Diaza[5]helicenes (benzo[*f*]naphtho[2,1-*c*]cinnolines)

2.8.1. Synthesis

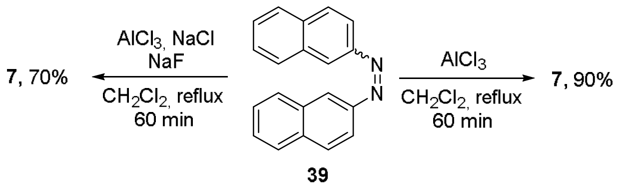
The first report regarding the synthesis of 7,8-diaza[5]helicene appeared already in 1903[34] when Meisenheimer *et al.* described a reaction of 2-nitronaphthalene **36** with Zn dust in an alcoholic solution of NaOH (Scheme 20). In addition to **7**, the formation of two other compounds was noticed. More than five decades later, in 1959,[35] Holt *et al.* reported a different approach that was based on Ullmann coupling of 1-iodo-2-nitronaphthalene **37** to binaphthyl **38** (38%). The latter was subsequently reduced with $LiAlH_4$ to 7,8-diaza[5]helicene **7**, which was isolated in 25% yield (Scheme 21). Yet other and more efficient procedures were developed.[36] One was based on intramolecular cyclization of 1,2-di(naphthalen-2-yl)diazene **39** (isomer was not specified) under Lewis acid condition using either $AlCl_3$ solution in dichloromethane. Another one relied on the cyclization in the melt of a mixture of $AlCl_3$, NaCl, and NaF (Scheme 22). The first procedure furnished **7** in 90% yield, whereas the second one in 70% yield.



Scheme 20. Formation of **7** from **36**.

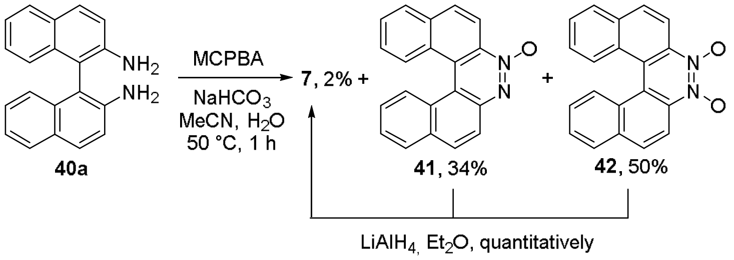


Scheme 21. Synthesis of **7** by Ullmann coupling of **37** followed by reduction.



Scheme 22. Synthesis of **7** by intramolecular cyclization of **39**.

Holt *et al.* also reported oxidation of [1,1'-binaphthalene]-2,2'-diamine **40a** to **7**, with a mixture of sodium perborate/hydrogen peroxide in acetic acid, but **7** was obtained in trace amounts only (not shown).[37] In 2008 Caronna *et al.* demonstrated that **7** can be prepared by direct oxidation of [1,1'-binaphthalene]-2,2'-diamine **40a**;[38] however, the desired compound **7** was obtained in just 2% yield (Scheme 23). The major products formed were *N*-oxide **41** and *N,N'*-dioxide **42** in 34% and 50% yields, respectively. Fortunately, both *N*-oxides can be quantitatively reduced to **7** by treatment with $LiAlH_4$. It should be noted that *N*-oxide **41** can also be prepared by a reaction of 2-nitronaphthalene with phosphine (PH_3) in an ethanolic solution of KOH as reported by Bellaart in 1965.[39]

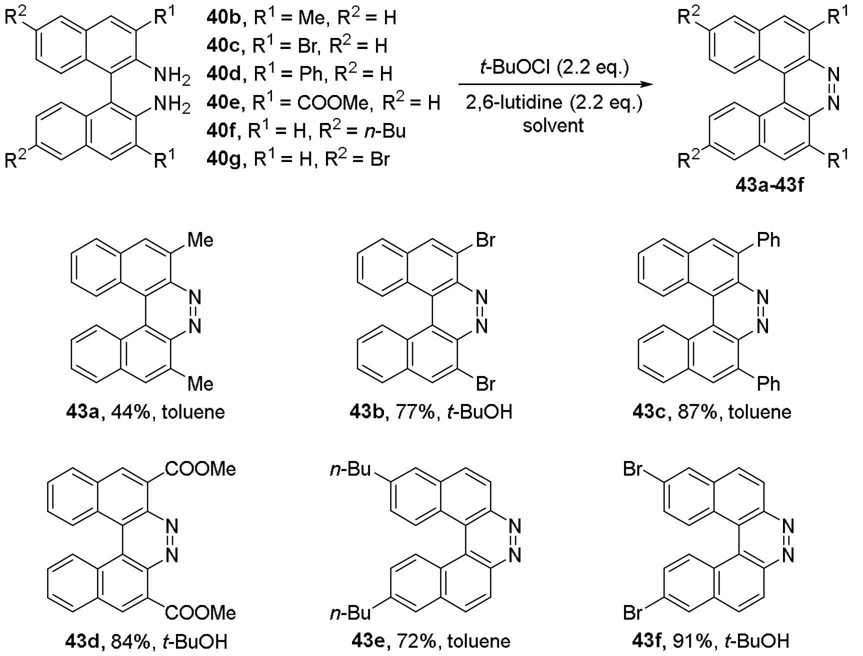


Scheme 23. Synthesis of **7** by oxidation of **40a**.

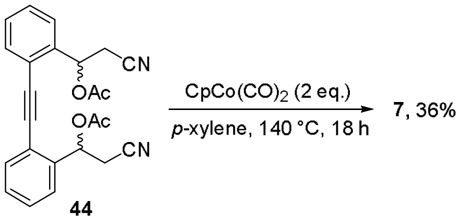
The oxidation approach was also explored by Takeda *et al.* in 2014,[40] who screened reactions of **40a** with different halogen-containing oxidants. It turned out that the best selectivity for the formation of **7** was obtained when *t*-BuOCl was used. Unlike when other oxidants were used, **7** was formed selectively in 89% yield (Scheme 24). Further tuning of reaction conditions allowed to increase the yield of **7** to 97%.[41] The improved oxidation conditions were used to synthesize variously substituted 7,8-diaza[5]helicenes **43a-43f** bearing bromo, carboxymethyl, alkyl, or phenyl substituents in very reasonable yields (44-91%) from the corresponding symmetrically substituted [1,1'-binaphthalene]-2,2'-diamines **42b-42g** (Scheme 25). Last, but not least, a methodology used for the synthesis of 7,8-diaza[5]helicenes was disclosed by Starý *et al.* in 2014,[42] who exploited a transition metal complex induced [2+2+2]-cyclotrimerization approach. Thus, heating of (ethyne-1,2-diylbis(2,1-phenylene))bis(2-cyanoethane-1,1-diyl) diacetate **44** with an excess of $CpCo(CO)_2$ (Vollhardt's catalyst) provided **7** in 36% isolated yield (Scheme 26). The yield could be improved to 52% by carrying out the reaction in a flow reactor (THF, 250 °C, 100 bar, flow rate: 0.5 $mLmin^{-1}$, residence time: 16 min). Other [n]helical aromatics were prepared by this methodology as well.

$$\mathbf{40a} \xrightarrow[t\text{-BuOH, rt, 3 h}]{t\text{-BuOCl}} \mathbf{7}\text{, 89\% (the sole product)}$$

Scheme 24. Synthesis of **7** by oxidation of **40a** with *t*-BuOCl.



Scheme 25. Synthesis of **43a-43f** by oxidation of **40b-40g**.



Scheme 26. Synthesis of **7** by using cyclotrimerization of **44**.

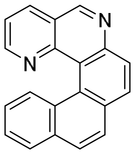
2.8.2. Properties and application

Further transformations of **7**, such as its reduction to **39**[34,43] and nitration to 7,12- and 7,14-dinitro-**7**,[44] were described. Compound **7** easily undergoes quaternization forming the respective pyridinium salts with methyl iodide.[24] UV-Vis absorption data for **7** and related compounds were reported as early as 1961,[45] and other studies followed later.[41,44,46,47] Blue fluorescence of **7** was noted in 1960,[43] and it has emission maxima at 457 and 445 nm depending on the solvent used.[47] Since **7** is a base, it forms a 1:1 salt with picric acid,[35,48] and a π–π complex with trinitrofluorenone.[48] Protonation of **7** was studied as well.[24,49,50] In addition, a TDDFT study of its low-lying excitation energies was carried out.[51] It is also worth of mentioning that **7** was found in soot among other polyaromatic hydrocarbons.[52]

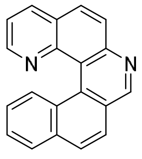
3. Unsymmetric *m,n*-diaza[5]helicenes

3.1. List of unsymmetric *m,n*-diaza[5]helicenes

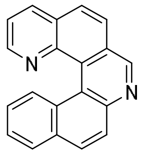
There are 42 possible regioisomeric *m,n*-diaza[5]helicenes. Nonetheless, only a few of them have been synthesized so far (Figure 3), and others remain to be prepared. In some cases, their basic framework is the essential part of larger molecular systems.



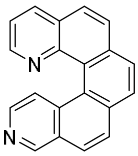
phenanthro[3,4-*h*][1,6]naphthyridine
1,6-diaza[5]helicene, **45**



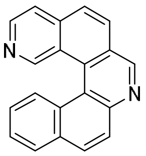
naphtho[2,1-*k*][1,7]phenanthroline
1,7-diaza[5]helicene, **46**



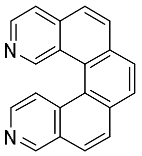
naphtho[2,1-*k*][1,8]phenanthroline
1,8-diaza[5]helicene, **47**



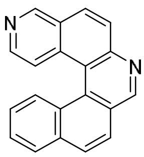
pyrido[3',4':7,8]naphtho[2,1-*h*]quinoline
1,12-diaza[5]helicene, **48**



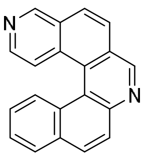
naphtho[2,1-*k*][2,8]phenanthroline
2,8-diaza[5]helicene, **49**



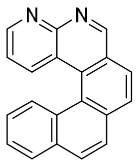
benzo[2,1-*f*:4,3-*h'*]diisoquinoline
2,12-diaza[5]helicene, **50**



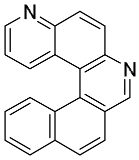
naphtho[2,1-*k*][3,7]phenanthroline
3,7-diaza[5]helicene, **51**



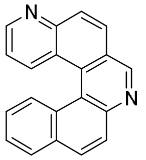
naphtho[1,2-*a*][3,8]phenanthroline
3,8-diaza[5]helicene, **52**



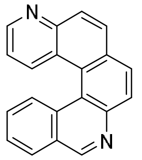
phenanthro[3,4-*c*][1,8]naphthyridine
4,5-diaza[5]helicene, **53**



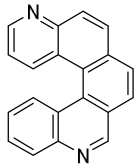
naphtho[1,2-*a*][4,7]phenanthroline
4,7-diaza[5]helicene, **54**



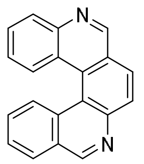
naphtho[1,2-*a*][3,7]phenanthroline
4,8-diaza[5]helicene, **55**



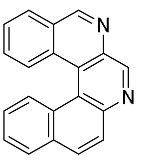
quinolino[5,6-*a*]phenanthridine
4,9-diaza[5]helicene, **56**



quinolino[6,5-*k*]phenanthridine
4,10-diaza[5]helicene, **57**



dibenzo[*a*,*k*][3,7]phenanthroline
5,9-diaza[5]helicene, **58**



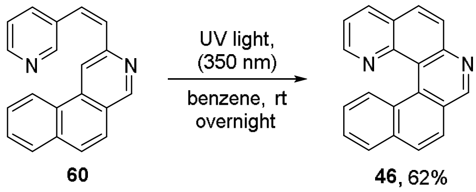
benzo[*c*]naphtho[1,2-*f*][1,7]naphthyridine
6,8-diaza[5]helicene, **59**

Figure 3. A list of known or prepared unsymmetric *m,n*-diaza[5]helicenes.

3.2. Synthesized *m*,*n*-diaza[5]helicenes

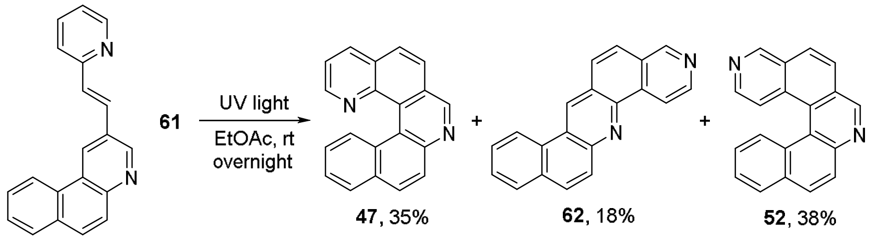
3.2.1. Synthesis

A synthesis of 1,7-diaza[5]helicene **46** was achieved *via* UV light (350 nm) induced photochemical cyclization of (*Z*)-2-(2-(pyridin-3-yl)vinyl)benzo[*f*]isoquinoline **60** by Macchi *et al.* in 2008.[17] It was obtained in 62% isolated yield (Scheme 27). Its structure was unequivocally confirmed by single crystal diffraction analysis.



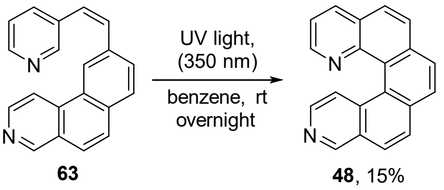
Scheme 27. Synthesis of **46** by photochemical cyclization of **60**.

In 2016, Clennan *et al.* reported that UV irradiation of (*E*)-2-(2-(pyridin-2-yl)vinyl)benzo[*f*]quinoline **61** (Scheme 28) furnished a mixture of three products: 1,8-diaza[5]helicene **47**, naphtho[2,1-*b*][1,8]phenanthroline **62**, and 3,8-diaza[5]helicene **52** in 35%, 18%, and 38% yields, respectively.[26,27]



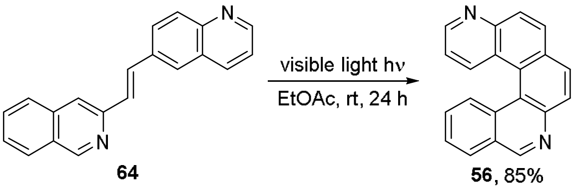
Scheme 28. Synthesis of diazahelicenes **47**, **62**, and **52** by photochemical cyclization of **61**.

1,12-Diaza-[5]helicene **48** was synthesized *via* UV light-induced photochemical cyclization of (*Z*)-9-(2-(pyridin-3-yl)vinyl)benzo[f]isoquinoline **63** as reported by Macchi *et al.* in 2008.[17] It was obtained only in 15% isolated yield (Scheme 29). The authors claim that the major product (70%) in the aforementioned photochemical cyclization was 1,14-diaza[5]helicene **1**, but the reported results clearly indicate that 4,11 regioisomer was formed. The structure of **48** was unequivocally confirmed by single crystal X-ray diffraction analysis.

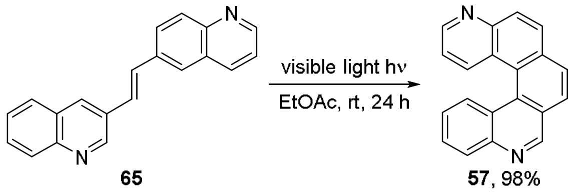


Scheme 29. Synthesis of **48** by photochemical cyclization of **63**.

4,9-Diaza[5]helicene **56** and 4,10-diaza[5]helicene **57** were synthesized *via* a photochemical pathway by Caronna *et al.* in 2005.[22] The former was prepared by irradiation of (*E*)-6-(2-(isoquinolin-3-yl)vinyl)quinoline **64** with visible light at room temperature for 24 h (Scheme 30) and was obtained in 85% isolated yield. The same reaction conditions were applied to (*E*)-6-(2-(quinolin-3-yl)vinyl)quinoline **65**, whose irradiation gave rise to the latter in 98% isolated yield (Scheme 31).



Scheme 30. Photochemical synthesis of 4,9-diaza[5]helicene **56** from **64**.



Scheme 31. Photochemical synthesis of 4,10-diaza[5]helicene **57** from **65**.

3.2.2. Properties and application

Proton affinities and electron distribution were calculated by using quantum-mechanical density functional for **5**.[24] Applications of several diazahelicenes including 3,8-diaza[5]helicene **52** in the fields of optoelectronic, semiconducting and photovoltaic devices with respect to advanced quantum chemical approaches have been described.[32]

3.3. Other *m,n*-diaza[5]helicenes

A synthesis and application of 1,6-diaza[5]helicene **45** is mentioned in a patent, but details are not available.[53] In an analogical manner syntheses and applications of 2,8-diaza[5]helicene **49**, 3,7-diaza[5]helicene **51**, 4,7-diaza[5]helicene **54**, 4,8-diaza[5]helicene **55**, 5,9-diaza[5]helicene **58**, and 6,8-diaza[5]helicene **59** derivatives were described in a patent.[54] However, no details are available.

Syntheses of 2,12-[5]helicene **50** and 4,5-diaza-[5]helicene **53** have not been reported. On the other hand, atomically precise hetero-graphene nanoribbons possessing the 2,12- and 4,5-diaza[5]helicene motifs in large π-conjugated aromatic molecular systems have been described.[55]

4. Selected physical properties of *m,n*-diaza[5]helicenes

In general, diaza[5]helicenes have slightly distorted helical structures because of steric interaction from hydrogen atoms attached in positions 1 and 14 or lone electron pairs when these positions are occupied by nitrogen atoms. The helical shape of diaza[5]helicenes is evident from their X-ray diffraction structures. The distortion of the molecular structures (helical pitch or lead) is defined by the sum of three dihedral angles ∠A-B-C-D+∠B-C-D-E+∠C-D-E-F [5]helicene's fjord region[56] (Figure 4 and Table 1). These values are similar to the one reported for the pristine [5]helicene (64.43°)[57], ranging from 61.31° to 68.11° depending on structural features. Worth mentioning is that 5,10-diaza[5]helicene **5** exists in three polymorphs. A higher helical pitch was observed in the case of diazonium salts **32a** and **32b**.

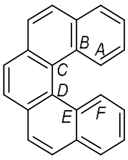


Figure 4. Numbering of atoms in internal dihedral angles.

Table 1. Helical pitches in symmetric *m,n*-diaza[5]helicenes.

m,n-diaza[5]helicene		CCDC	Helical pitch (°)[a,b]	References
[5]helicene		2007122	64.43	57
1,14-diaza[5]helicene	**1**	1182380	64.14	10
4,11-diaza[5]helicene	**4**	686815	65.80	17
5,10-diaza[5]helicene	**5**	686816	62.62	17
	5	686817	61.31	17
	5	686818	63.05	17
	29a	906647	61.25	30
	29c	906648	65.22	30
	32a	989355	68.11	25
	32b	1558366	66.65	29
7,8-diaza[5]helicene	**7**	859770	64.24	24
1,7-diaza[5]helicene	**46**	686819	61.63	17
1,12-diaza[5]helicene	**48**	686820	62.64	17

[a] See the definition above. [b] The sums of dihedral angles were obtained from corresponding CIF files.

As far as the configurational stability of diaza[5]helicenes is concerned, it is expected that it will be similar to that of the pristine [5]helicene. The recorded racemization barriers are indeed very similar as indicated by calculated values in Table 2. Interestingly, experimental data for any of the prepared diaza[5]helicene are not available assuming that they were not measured. Nonetheless, calculated values are available for several regioisomeric diaza[5]helicenes such as **1**, **2**, and **5**. The calculated values more or less resemble the value reported for the pristine [5]helicene indicating rapid room temperature conformational deformation that is likely to limit their lifetimes to minutes making resolution studies complicated and perhaps impractical.

Table 2. Racemization barriers for *m,n*-diaza[5]helicenes.

m,n-diaza[5]helicene		$\Delta G^{\neq}_{\mathrm{calc}}$ (kcal·mol^{-1})	$\Delta G^{\neq}_{\mathrm{exp}}$ (kcal·mol^{-1})	References
[5]helicene		22.5	24.1	25,58
1,14	**1**	14.1	-	16
	1·H$^+$	4.7	-	16
	1·2H$^+$	24.2	-	16
2,13	**2**	21.4	-	16
	2·H$^+$	15.7	-	16
	2·2H$^+$	20.5	-	16
5,10	**5**	19.9	-	25

Only a handful of information on the photophysical properties of *m,n*-diaza[5]helicenes is available. In general, *m,n*-diaza[5]helicenes have fluorescence in the blue light region as indicated by data in Table 3.

Table 3. Fluorescence emission maxima of selected *m,n*-diaza[5]helicenes.

m,n-diaza[5]helicene	λ_{em} (nm)	solvent	*Φ* (%)	References
2	443 and 472	EtOH	-[a]	18
5	412 and 438	EtOH	-[a]	18
6	424 and 438	EtOH	-[a]	18
7	457	MTHF	1.2	47
7	445	ethanol	0.7	47
66 (Figure 5)	410	chloroform	-[a]	59

[a] Not available.

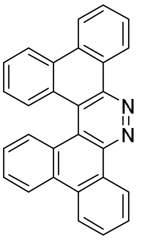


Figure 5. Dibenzo[*f,h*]phenanthro[9,10-*c*]cinnoline **66**.

5. Conclusion and perspectives

In conclusion, several approaches towards symmetric or unsymmetric *m,n*-diaza[5]helicenes have been developed over the last hundred years. However, not all synthetic pathways have been exploited yet and the area of azahelicenes synthesis is still opened for further development and exploratory research. Albeit *m,n*-diaza[5]helicenes have shown an interesting potential for various applications thanks to their physical properties, this field is still rather neglected and only scant information is available. Despite the aforementioned, there is no doubt that these fascinating compounds will attract further and wider attention resulting in the development of new synthetic procedures together with studies of their physical properties and potential applications.

As far as the development of new synthetic procedures towards *m,n*-diaza[n]helicenes (n≥5) is concerned, a pathway relying on ring-expansion methodologies of a five-membered ring resulting in the formation of pyridine moiety could be an interesting option. Namely, regioselective two-fold ring expansion of indeno[2,1-*c*]fluorene-5,8-diones utilizing Schmidt rearrangement could open a route for the preparation of substituted *m,n*-diaza[5]helicenes with *m*=5, *n*=9 or *m*=5, *n*=10 or *m*=6, *n*=9. This approach would have several advantages. First, efficient syntheses of variously substituted helical indeno[2,1-*c*]fluorene-5,8-dione having [5]-, [7]-, [9]-helical scaffolds have been developed.[60,61] Second, their enantioselective synthesis with a high level of asymmetric induction was reported as well.[62] In this respect, successful conversion of highly enantioenriched helical indeno[2,1-*c*]fluorene-5,8-diones to the corresponding diazahelicenes would enable their enantioselective synthesis, an achievement that has not been reached yet. Third, it has been demonstrated that even simple 5,8-dihydroindeno[2,1-*c*]fluorenes readily undergo rearrangements to other aromatic compounds.[63,64] Fourth, a successful example of an application of Schmidt rearrangement for conversion of 9*H*-cyclopenta[1,2-*c*:4,3-*c'*]diphenanthren-9-one to a substituted 9-aza[7]helicene was reported indicating the synthetic feasibility of such a process.[65] The above-mentioned set of data seems to provide a reasonable rationale for exploratory endeavors in this direction.

Acknowledgement

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