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# Camphor-Annulated Tripyrazinosubporphyrazinatoboron(III) Chloride

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Dedicated to the memory of Academician Oskar Iosifovich Koifman

*Series of porphyrazinoids containing fused chiral camphor units (tetrapyrazinoporphyrazines, hemiporphyrazines and [30]trithiadodecaazahexaphyrine) was expanded by novel subphthalocyanane azaanalogue – boron(III) tripyrazinosubporphyrazine which was prepared by trimerization of the corresponding pyrazine-2,3-dicarbonitrile derived by condensation of 1S(+)-camphorquinone and diaminomaleodinitrile in the presence of boron trichloride in o-dichlorobenzene. 1H NMR spectroscopy evidence that subporphyrazine is formed as a mixture of randomers with different orientation of 1S-camphor units, which was characterized by MALDI mass-spectrometry electronic absorption and emission spectroscopy.*

**Keywords:** Boron(III) subporphyrazines, camphorquinone, pyrazine-dicarbonitrile, spectroscopy, fluorescence.

# Камфорно-аннелированный трипиразиносубпорфиразинат бора(III)

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Посвящается памяти академика Оскара Иосифовича Койфмана

*Серия порфиразиноидов, содержащих конденсированные хиральные камфорные фрагменты (тетрапиразинопорфиразины, гемипорфиразины и [30]тритиадодекаазагексафирин), была дополнена новым субфталоцианиновым азааналогом – трипиразиносубпорфиразином бора(III), который был синтезирован тримеризацией в присутствии трихлорида бора в о-дихлорбензоле соответствующего пиразин-2,3-дикарбонитрила, полученного конденсацией 1S(+)-камфорхинона и диаминомалеодинитрила,. Спектроскопия ЯМР $^{1}$H свидетельствует о том, что субпорфиразин образуется в виде смеси рандомеров с различной ориентацией 1S-камфорных фрагментов, которая была охарактеризована с помощью масс-спектрометрии MALDI, электронной абсорбционной и эмиссионной спектроскопии.*

**Ключевые слова:** Субпорфиразины бора(III), камфорохинон, пиразиндикарбонитрил, спектроскопия, флуоресценция.

Subphthalocyanine (sPc, Chart 1), first obtained by Meller and Ossco in 1972,[1] is a cone-shape macroheterocycle in which three isoindole fragments are connected by *meso*-nitrogen bridges located around a tetrahedral boron atom bearing an axial substituent. A key feature of such contracted phthalocyanine-type macrocycles is that they are known only as boron(III) derivatives.[2] Subphthalocyanines and their analogues are actively studied as promising materials for organic photovoltaics,[3] fluorescence diagnostics[4] and photodynamic therapy.[5] Application of sPcs in these areas is determined by their unique optical properties and the absence of aggregation in solutions.

The structure of subphthalocyanines can be modified by annulation of pyrazine fragments instead of benzene

rings which leads to tripyrazinosubporphyrazines ($Pyz_3sPz$, Chart 1). The unsubstituted boron(III) complex was obtained from pyrazine-2,3-dicarbonitrile and $BCl_3$ with very low yield (0.3%).[6] Methyl and ethyl substituted $Pyz_3sPz$ were formed from the corresponding 5,6-dialkylpyrazine-2,3-dicarbonitriles only in trace amounts and cannot be isolated from the reaction mixture. Higher yields of $Pyz_3sPz$ were obtained from dinitriles bearing either aryl groups or saturated quaternary carbon atom adjacent to pyrazine ring. Thus, hexaphenyl substituted derivative $Ph_6Pyz_3sPz$ was obtained in 6.2% yield.[6] For *tert*-butyl substituted compound $^tBu_3Pyz_3sPz$ two positional isomers having $C_1$ and $C_3$ symmetry were obtained and effectively separated by column chromatography with a total yield of 7%.[7] A symmetric $Pyz_3sPz$ with 2,3-fused 1,1,4,4-tetramethylcyclohexane fragments was obtained in 35% yield.[8]

It is of great interest to introduce chiral substituents into macrocycles in order to obtain optically active molecules, which could be potentially suitable for use as sensors for chiral biological molecules, or for selective interaction with biopolymers. Phthalocyanines and their analogues with chiral fragments attract considerable attention.[9,10] Subporphyrazines with intrinsic chirality could be obtained from non-symmetrical dicarbonitriles, *e.g.* from thionaphthene-2,3-dicarbonitrile[11] or benzothiazole-5,6-dicarbonitrile.[12] Chirality can be introduced in the dinitrile precursor itself. Camphor and its derivatives which are available as pure enantiomers are frequently used for introduction of chirality in different molecular systems.[13,14] Thus, pyrazine-2,3-dicarbonitriles with fused chiral camphor moiety (1*R*-(+)- and 1*S*-(-)-$CamPyz(CN)_2$) were prepared by condensation of 1*R*-(-)- and 1*S*-(+)-enantiomers of camphorquinone (or their racemic mixture) with diaminomaleonitrile (DAMN) in ethanol[15] or better in acetic acid.[16] These chiral dinitriles were first used in 1998 by Professor Kobayashi for preparation of optically active camphor-fused tetrapyrazinoporphyrazine ($CamPyz_4PzH_2$) and its $Cu^{II}$ complex.[20] Later complexes with $Mg^{II}$, $Ni^{II}$ [17] and $Si^{IV}$ [18,19] were also prepared (Scheme 1).

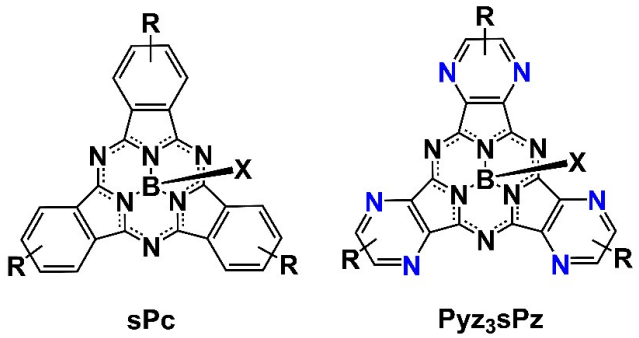
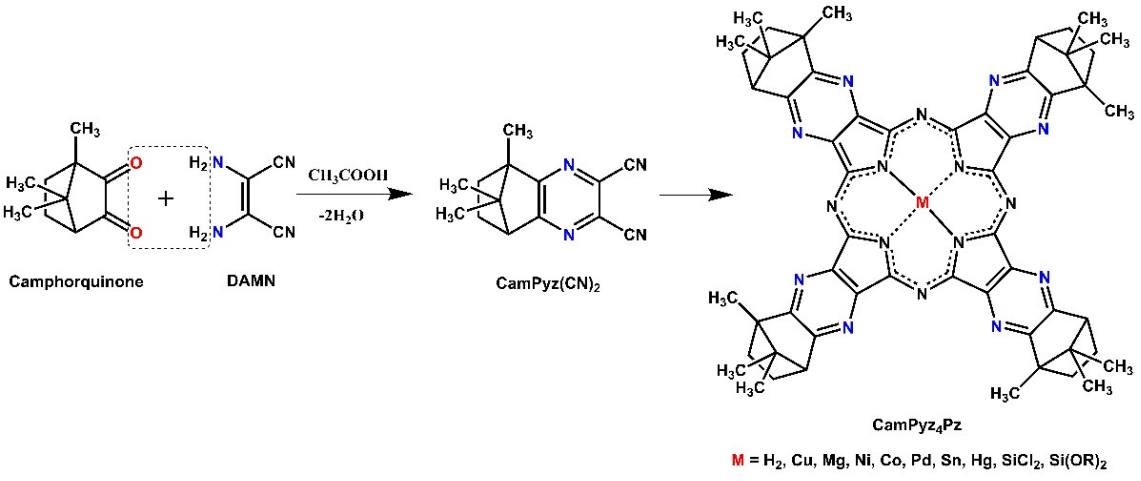



**Chart 1.** Structure of subphthalocyanine (sPc) and tripyrazinosubporphyrazine ($Pyz_3sPz$).

In 2017 the Russian group from the *Research Institute of Macroheterocycles* founded by Professor Koifman has prepared $Cu^{II}$, $Ni^{II}$, $Co^{II}$, $Pd^{II}$, $Sn^{II}$ and $Hg^{II}$ complexes of tetrapyrazinoporphyrazine by template tetramerization of the racemic $CamPyz(CN)_2$ in the presence of the corresponding metal salts.[20] In development of this work other camphor-fused macrocycles were also synthesized. Thus, hemiporphyrazine ($CamPyz_2HemPz$, Chart 2) with two camphor fragments was obtained using microwave activated synthetic procedure from the $CamPyz(CN)_2$ (*R*-(+) form or racemic mixture) and *m*-phenylenediamine and used for induction of the chiral nematic phase in solutions of 4-*n*-alkyloxy-4′-cyanobiphenyles.[21] In the reaction of $CamPyz(CN)_2$ (*R*-(+) or *S*-(-)-enantiomers) with 2,5-diamino-1,3,4-thiadiazole the first chiral [30]trithiadodecaazahexaphyrins ($CamPyz_3HexPhyr$, Chart 2) were obtained as a mixture of enantio-pure regioisomers with $C_1$ and $C_3$ symmetry, which were separated by chromatography.[22]

In this communication, we report the synthesis and spectral characterization of a novel subphthalocyanine aza-analogue, tripyrazinosubporphyrazinatoboron(III) chloride with fused (1*S*)-camphor moieties, [$CamPyz_3sPz$].




**Scheme 1.** General scheme for the synthesis of tetrapyrazinoporphyrazines with camphor units (enantiomer with (1*S*)-configuration is shown).

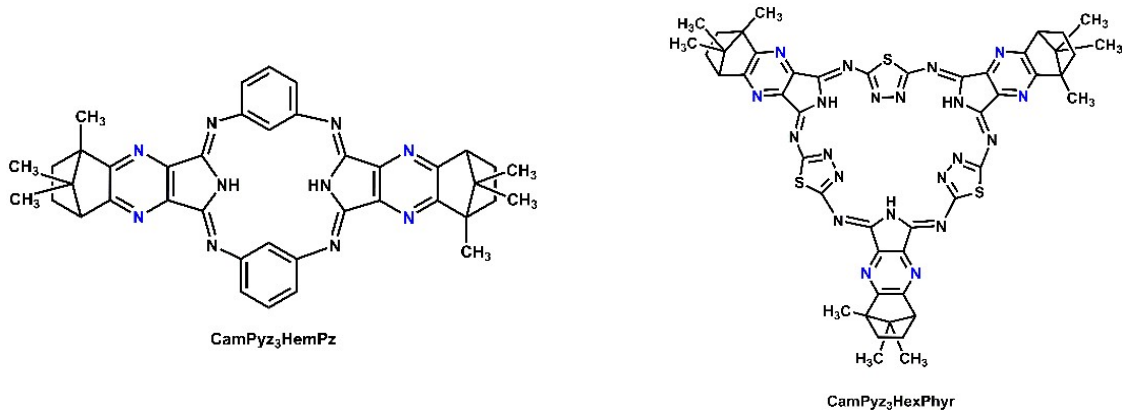
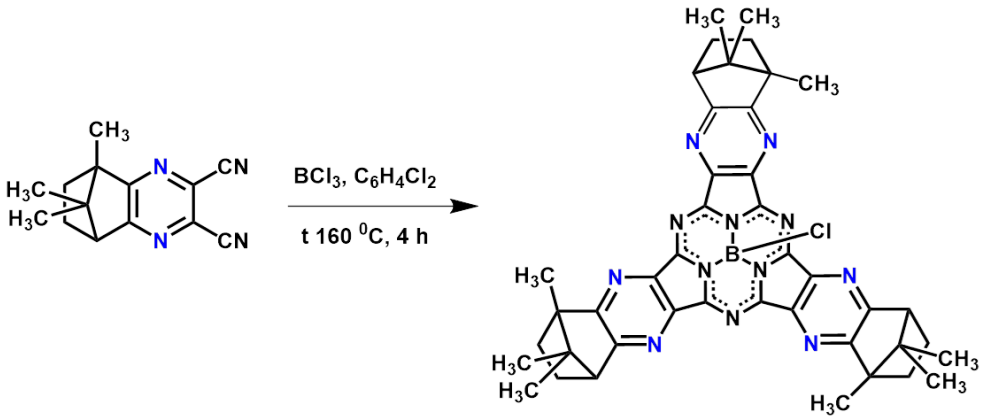



**Chart 2.** Structures of hemiporphyrazine (left) and [30]trithiadodecaazahexaphyrine (right) containing camphor-annulated pyrazine fragments.




**Scheme 2.** Synthesis of camphor-annelated trypyrazinosubporphyrazine boron(III), [CamPyz$_3$sPz].

Camphor-annulated pyrazine-2,3-dicarbonitrile ((1*S*)-(–)-enantiomer, 0.3 g, 0.0013 mol), prepared by condensation of (1*S*)-(+)-camphorquinone and diaminomaleodinitrile (DAMN) in glacial acetic acid under reflux,[16] was dissolved in *o*-dichlorobenzene (DCB, 1.5 mL) and after purging with argon solution of boron(III) trichloride (1.5 mL of 1 M in *p*-xylene) was added. The reaction mixture immediately changed color to dark red and then turned brown upon heating under reflux for 4 h. The progress of the reaction was monitored by TLC till appearance of characteristic pink spot typical for subporphyrazine. After cooling, the reaction mixture was poured into hexane and formed precipitate was purified using column chromatography on silica gel. Intermediates and by-products were extracted with $CH_2Cl_2$, and the target subporphyrazine [CamPyz$_3$sPz] was eluted with a mixture $CH_2Cl_2$:EtOAc (10:1).[#]

The constitution of the product is confirmed by LDI-mass spectrum which contains the intense peak at 726.3 Da and minor peak at 762.3 Da corresponding to the positive molecular ions $[M\text{-}Cl]^+$ and $[M+H]^+$, respectively (Figure 1). Such fragmentation with loss of the axial halogen atom is typical for subporphyrazines and subphthalocyanines.

Comparison of the $^1$H NMR spectrum recorded for [CamPyz$_3$sPz] with the spectral parameters of other compounds containing camphor fragment fused to pyrazine ring (Table 1) reveals some structural peculiarities. Since the dinitrile precursor is not symmetrical, its template cyclotrimerization can lead to formation of four positional isomers (randomers) of [CamPyz$_3$sPz], differing in the location of the $^7$C bridge in respect to the conical subporphyrazine macrocycle and the central boron atom.

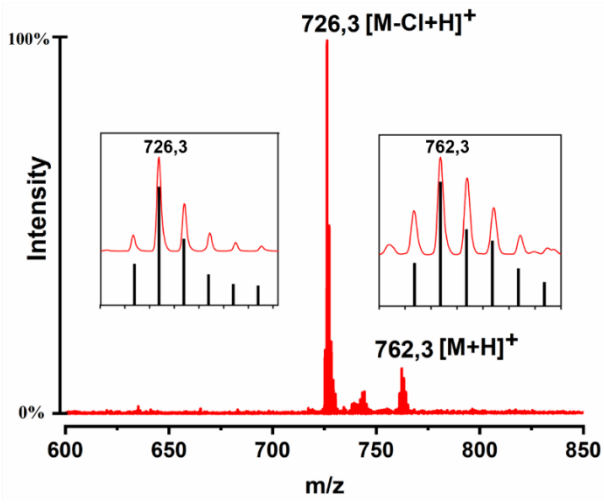



**Figure 1.** Mass spectrum of [CamPyz$_3$sPz] in the positive region. The inserts show the calculated isotope distribution for the molecular ions.

One can consider two symmetrical $C_3$ isomers and two $C_1$ isomers. In $C_3(\Delta_3)$ isomer one all three $^7$C atoms are located similarly with the boron atom on the convex side and in another $C_3(\nabla_3)$ isomer on the opposite concave side of the macrocycle. Less symmetrical isomers can have $C_1(\Delta_2\nabla)$ or $C_1(\Delta\nabla_2)$ structure.

In the case of dinitrile [CamPyz(CN)$_2$] and derived planar macrocyclic compounds (Si$^{IV}$ porphyrazine complex, hemiporphyrazine and [30]trithiadodecaazahexaphyrin) the methyl groups attached to the quaternary $^7$C atoms of the fused camphor moiety give singlets in the strong field at ~0.6 ppm for *endo*-$^7$CH$_3$ located above the pyrazine ring and at ~1.1 ppm for *exo*-$^7$CH$_3$. Protons of the methylene groups in the 5 and 6 positions are diastereotopic and appear as broad multiplets at ~2.3–2.4 and ~2.0–2.2 ppm for *exo*-$^5$CH$_2$ and *exo*-$^6$CH$_2$, while resonances of *endo*-$^{5,6}$CH$_2$ overlap with $^3$CH$_3$ singlet in the 1.1–1.4 ppm region. Protons of the $^1$CH group which are nearest to the pyrazine ring give doublet at 3.1–3.4 ppm with typical *gauche* constant $^3J \sim 4.5$ Hz.

The $^1$H NMR spectrum of the obtained subporphyrazine [CamPyz$_3$sPz] provides clear evidence about presence of randomers with different orientation of camphor moieties. The protons of *endo*-$^7$CH$_3$ group appear as four closely lying singlets at 0.320, 0.330, 0.344 and 0.346 ppm and corresponding *exo*-$^7$CH$_3$ give two close signals at 0.973 and 0.978 ppm and overlapping $^3$CH$_3$ and *endo*-$^{5,6}$CH$_2$ signals at 1.10–1.16 ppm. Protons of *exo*-$^5$CH$_2$ and *exo*-$^6$CH$_2$ appear as broad multiplets at ~2.3 and ~2.1 ppm and $^1$CH group, which is nearest to the macrocycle, gives closely lying doublets at 3.3–3.4 ppm with *gauche* constant $^3J \sim 4.3$ Hz.

The high-field shift observed for the *endo*-$^7$CH$_3$ resonances (*ca* 0.3 ppm) is indicative about their stronger shielding by aromatic current of the pyrazine ring than in the dinitrile and in planar macrocycles. This can be explained by the location of the $^7$C-bridge on the concave side of the macrocycle and the presence of four signals correlates with four possible arrangements in one symmetrical $C_3(\nabla_3)$ and two low-symmetry $C_1(\Delta_2\nabla)$ or $C_1(\Delta\nabla_2)$ randomers. Series of signals in the weaker field at 1.21–1.24, 1.01–1.03 and 0.62–0.72 ppm can be very likely assigned to the protons attached to the convex ($\Delta$) oriented camphor units ($^3$CH$_3$/*endo*-$^{5,6}$CH$_2$, *exo*-$^7$CH$_3$ and *endo*-$^7$CH$_3$, respectively). Since their integral intensity is about half the intensity of concavely ($\nabla$) oriented camphor units, formation of subporphyrazine randomers with predominant convex orientation $C_1(\Delta_2\nabla)$ and $C_3(\Delta_3)$ during template cyclotrimerization is evidently less favorable.

It should be noted that $^1$H NMR data presented for the planar porphyrazine [CamPyz$_4$PzSi(OH)$_2$] evidence about formation of only one most symmetrical randomer,[19] and in the case of planar [30]hexaphyrin two randomers ($C_1$ and $C_3$) were observed.[22]

The electronic absorption spectrum of [CamPyz$_3$sPz] (Figure 2) contains intense absorption bands at 525 and 300 nm which are typical for subphthalocyanines[2] and subporphyrazines with fused heterocycles,[6-8,23,24] and appear due to $\pi\rightarrow\pi^*$ transitions of the subporphyrazine $\pi$-chromophore – HOMO → LUMO (Q band) and HOMO-1 → LUMO (B band) (Figure 2). In addition, the medium intensity band is seen at 333 nm. The maximum of the Q band is located at a slightly shorter wavelength (by 5–10 nm) than in the case of unsubstituted [Pyz$_3$sPz], its tri-*tert*-butyl substituted and 1,1,4,4-tetramethylcyclohexane fused derivatives, [*t*Bu$_3$Pyz$_3$sPz] and [Me$_4$cHxPyz$_3$sPz]; and by 25 nm more hypsocromically than in hexaphenyl substituted compound [Ph$_6$Pyz$_3$sPz] (Table 2). Interestingly that the additional band observed at 333 nm is not seen in the spectrum of unsubstituted [Pyz$_3$sPz], but is present as a shoulder for [*t*Bu$_3$Pyz$_3$sPz] and as a similar maximum for [Me$_4$cHxPyz$_3$sPz]. The origin of this band is different from the band at 386 nm observed for [Ph$_6$Pyz$_3$sPz] due to charge transfer transition from phenyl rings to subporphyrazine macrocycle. Most likely two bands in the UV region are similar to the $B_1$ and $B_2$ bands observed for hexachlorinated subporphyrazine [Cl$_6$Pyz$_3$sPz] and appear due to excited states involving electronic transitions from two $a_1$-type orbitals ($2a_1\rightarrow e_g^*$ and $3a_1\rightarrow e_g^*$) which lye closely in unsubstituted subporphyrazine, but are differentiated and gain intensity upon peripheral alkylation or chlorination.

**Table 1.** Chemical shifts (δ, ppm) of proton resonances in the camphor fragments.

| Compound | 4-CH | 5-CH$_2$ (*exo*) | 6-CH$_2$ (*exo*) | 5,6-CH$_2$ (*endo*) | 1-CH$_3$ | 7-CH$_3$ (*exo*) | 7-CH$_3$- (*endo*) | Ref. |
|---|---|---|---|---|---|---|---|---|
| CamPyz(CN)$_2$ | 3.14d (4.5Hz) | 2.38–2.35m | 2.15–2.10m | 1.25, 1.28 | 1.36s | 1.11s | 0.60s | [16,22] |
| [CamPyz$_4$PzSi(OH)$_2$] | 3.15d (4.5Hz) | 2.40–2.32m | 2.12p (10Hz) | 1.31q (10Hz) | 1.36s | 1.11s | 0.60s | [19] |
| [CamPyz$_2$HemiPz] | 3.25s | 2.36m | 2.10 | 1.30m | 1.46–1.38m | 1.13s | 0.69s | [21] |
| $C_3$ [CamPyz$_3$HxPhyr] | 3.15 (4.3Hz) | 2.34–2.28 | 1.96–1.89 | 1.32–1.29; 1.36–1.34 | 1.40 | 1.06s | 0.60s | [22] |
| $C_1$ [CamPyz$_3$HxPhyr] | 3.24 | 2.43–2.37 | 2.04–1.99 | 1.43, 1.41 | 1.50 | 1.15 | 0.69 | [22] |
| Mixture of isomers | 3.16 | 2.31–2.38 | 2.12–2.07 | 1.41–1.42 | | 1.08 | 0.66, 0.64, 0.63, 0.61 | [22] |
| [CamPyz$_3$sPz] ($\nabla$) fragments | 3.36d, 3.39d (4.2 Hz) | 2.31 | 2.07 | 1.15 | 1.17 | 0.97, 0.98 | 0.33, 0.32, 0.340, 0.345 | This work |
| [CamPyz$_3$sPz] ($\Delta$) fragments | 3.43m | 2.4–2.0 | | 1.1–1.2 (1.22–1.23) | | 1.02, 1.03 | 0.62–0.72 | This work |

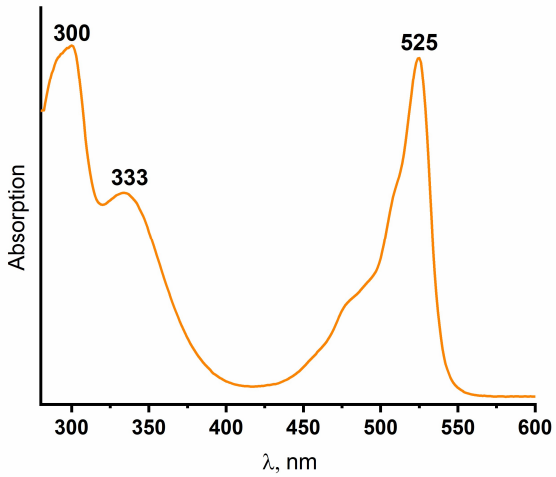



**Figure 2.** Electronic absorption spectrum of [CamPyz$_3$sPz] in $CH_3CN$.

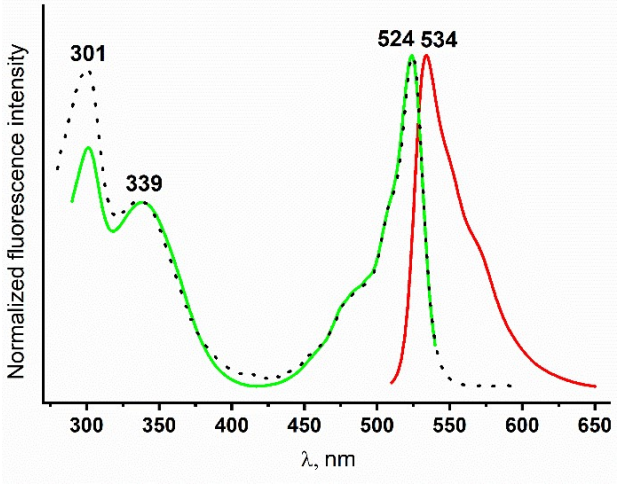



**Figure 3.** Fluorescence emission ($\lambda_{ex}$=500 nm, red line) and excitation ($\lambda_{em}$=550 nm, green line) spectra of [CamPyz$_3$sPz] in $CH_2Cl_2$. Absorption spectrum is shown by dotted line.

**Table 2.** Spectral luminescence properties of pyrazine fused boron(III) subporphyrazines in dichloromethane.

| Subporphyrazine | Absorption, λ (nm) | | | Fluorescence | | Ref. |
|---|---|---|---|---|---|---|
| | Soret region | | Q band | $\lambda_{em}$ (nm) | $\Phi_F$ | |
| [Pyz$_3$sPz] | 306 | | 532 | 542 | 0.15 | [6] |
| [$^t$Bu$_3$Pyz$_3$sPz] | 295 | 330sh | 530 | 540 | 0.37 ($C_1$), 0.28 ($C_3$) | [7] |
| [Me$_4$cHxPyz$_3$sPz] | 303 | 334 | 534 | 546 | 0.19 | [8] |
| [CamPyz$_3$sPz] | 303 | 333 | 525 | 534 | 0.31 | This work |
| [Ph$_6$Pyz$_3$sPz] | 310 | 386 | 551 | 560 | 0.31 | [6] |
| [Cl$_6$Pyz$_3$sPz] | 311 | 340 | 535 | 544 | 0.20 | [23] |

The fluorescence spectrum for [CamPyz$_3$sPz] in $CH_2Cl_2$ is shown in Figure 3. The emission band has mirror symmetry with the Q band in the excitation spectrum, which is almost identical to the absorption spectrum. The value of the Stokes shift is ~10 nm and indicates that only small geometric rearrangements occur in excited state, which is typical for subphthalocyanines and subporphyrazines. The fluorescence quantum yield values $\Phi_F$ for [CamPyz$_3$sPz] in $CH_2Cl_2$ are $\Phi_F$ = 0.31 and $\Phi_F$ = 0.39 in toluene.[†] [] This value is close to data determined for other alkyl and aryl substituted tripyrazinoporphyrazines (Table 2). For unsubstituted species [Pyz$_3$sPz] $\Phi_F$ values are lower due to aggregation effects and for and hexachloro derivative [Cl$_6$Pyz$_3$sPz] due to heavy atom effect of chlorine atoms.

Thus, we have synthesized a new azaanalogue of subphthalocyanine containing fused chiral *S*-camphor units and studied its spectral and fluorescent properties. The study of the analogues with *R*-camphor units is in progress.

## Notes

[#] *[CamPyz$_3$sPz]*. Yield 10%. $R_f$ = 0.68 (15% EtOAc in $CHCl_3$). LDI-mass spectrum: *m/z* = 726.3 (100%) $[M\text{-}Cl]^+$ (calcd. 726.38), 762.3 (10%) $[M+H]^+$ (calcd. 761.35). UV-Vis ($CHCl_3$) $\lambda_{max}$ nm (lgε): 302 (4.23), 333 (3.99), 525 (4.17).

[†] Fluorescence quantum yields ($\Phi_F$) were determined by a comparative method using Rhodamine 6G as a reference ($\Phi_F^R$=0.94 in ethanol[25]) according to the equation: $\Phi_F^S=\Phi_F^R(F^S/F^R)(A^R/A^S)(n^S/n^R)^2$, where $F$ is the integrated area under the emission spectrum, $A$ is the absorbance at the excitation wavelength (500 nm), $n$ is the refraction index of the solvent, superscripts R and S correspond to the reference and the sample, respectively. The emission spectra were corrected for the instruments response. Absorption in the Q-band region was kept below 0.1 in order to eliminate an inner filter effect. All measurements were performed three times and presented data represent the mean values of three experiments with the estimated error ± 10%.

## References

1. Meller A., Ossko A. *Monatsh. Chem.* **1972**, *103*, 150–155.
2. Claessens C.G., Gonzalez-Rodríguez D., Torres T. *Chem. Rev.* **2014**, *4*, 2192–2277.
3. Morse G.E., Bender T.P. *ACS Appl. Mater. Inter.* **2012**, *4*, 5055–5068.
4. Bernhard Y., Winckler P., Chassagnon R., Richard P., Gigot E., Perrier-Cornet J.M., Decreau R.A. *Chem. Commun.* **2014**, *50*, 13975–13978.
5. Demuth J., Gallego L., Kozlikova M., Machacek M., Kucera R., Torres T. *Med. Chem.* **2021**, *64*, 17436–17447.
6. Stuzhin P.A., Skvortsov I.A., Zhabanov Y.A., Somov N.V., Razgonyaev O.V., Nikitin I.A., Koifman O.I. *Dyes Pigm.* **2019**, *162*, 888–897.
7. Panteleev A.S., Skvortsov I.A., Koifman O.I., Stuzhin P.A. *J. Porphyrins Phthalocyanines* **2021**, *25*, 282–288.
8. Liebold M., Sharikow E., Seikel E., Trombach L., Harms K., Zimcik P., Sundermeyer J. *Org. Biomol. Chem.* **2018**, *16*, 6586–6599.
9. Kobayashi N. *Coord. Chem. Rev.* **2001**, *219*, 99–123.
10. Lu H., Kobayashi N. *Chem. Rev.* **2016**, *116*, 6184–6261.

11. Shang H., Zhao L., Qi D., Chen C., Jiang J. *Chem. Eur. J.* **2014**, *20*, 16266–16272.
12. Nečedová M.M., Magdolen P., Fülöpová A., Cigáň M., Zahradník P., Filo J. *Dyes Pigm.* **2016**, *130*, 24–36.
13. Adamenko E.N., Frolova L.L., Panteleeva M.V., Kuchin A.V. *Chem. Nat. Compd.* **2007**, *43*, 59–62.
14. Anjaneyulu B., Saini N. *Curr. Org. Chem.* **2021**, *25*, 1404–1428.
15. Kobayashi N., Nevin W. *Chem. Lett.* **1998**, *27*, 851–852.
16. Filatov M., Trukhina N., Efimova V., Islyaikin M. *Macroheterocycles* **2013**, *6*, 82–85.
17. Jang C.K., Byun S.H., Kim, S.H., Lee D.K., Jaung J.Y. *J. Porphyrins Phthalocyanines* **2009**, *13*, 794–797.
18. Park J.M, Jung C.Y., Song C.J., Jaung J.Y. *Inorg. Chem. Commun.* **2015**, *62*, 64–66.
19. Kolarova M., Zimcik P., Ivanova S., Miletin M., Novakova V. *J. Porphyrins Phthalocyanines* **2023**, *27*, 444–451.
20. Kuvshinov G.V., Ziyadova T.M., Kuvshinova S.A., Koifman O.I. *Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol. [ChemChemTech]* **2017**, *60*(4), 60−67.
21. Burmistrov V.A., Novikov I.V., Aleksandriiskii V.V., Islyaikin M.K., Kuznetsova A.S., Koifman O.I. *J. Mol. Liq.* **2019**, *287*, 110961.
22. Filatov M.S., Trukhina O.N., Rodríguez-Morgade M.S., Islyaikin M.K., Koifman O.I., Torres T. *J. Porphyrins Phthalocyanines* **2014**, *18*, 1014–1020.
23. Skvortsov I.A., Kovkova U.P., Zhabanov Y.A., Khodov I.A., Somov N.V., Pakhomov G.L., Stuzhin P.A. *Dyes Pigm.* **2021**, *185*, 108944.
24. Hamdoush M., Ivanova S.S., Pakhomov G.L., Stuzhin P.A. *Macroheterocycles* **2016**, *9*, 230–233.
25. Kubin R.F., Fletcher A.N. *J. Lumin.* **1982**, *27*, 455–462.

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