Макрогетероциклы
http://macroheterocycles.isuct.ru

DOI: 10.6060/mhc213990z

Modification of β−Octaethylporphyrin *via* Insertion of Amino and Azino Groups into *meso*−Positions

Valeriia D. Andreeva,[a] Gelii V. Ponomarev,[b] Alena O. Shkirdova,[a] Vladimir S. Tyurin,[a@1] and Ilya A. Zamilatskov[a,c@2]

[a]*A.N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, 119071 Moscow, Russian Federation*
[b]*Orekhovich Institute of Biomedical Chemistry, 119121 Moscow, Russian Federation*
[c]*A.N. Kosygin Russian State University, Department of Organic Chemistry, 119071 Moscow, Russian Federation*
[@1]*Corresponding author E-mail: vst-1970@mail.ru*
[@2]*Corresponding author E-mail: joz@mail.ru*

The functionalization of Ni(II) β-octaethylporphyrin was performed by introducing various amino and azino groups into meso-positions. Amino, n-propylamino, and trifluoromethylacetylamino groups were used as electron donor substituents, while azino group was inserted as an electron acceptor. The azine fragment was inserted through formylation followed by reaction with hydrazine and then with aromatic aldehydes, and the corresponding azine derivatives of p-nitrophenylbenzaldehyde and methyl pyropheophorbide d were obtained. It was found that under the conditions of formylation of meso-(trifluoroacetamido)-β-octaethylporphyrin, the amide fragment was oxidized to form hydroxamic acid. As a result of substitution of meso-positions of β-octaethylporphyrin, new functionalized porphyrin derivatives with significantly altered electron-optical properties were obtained. In particular, the azine bridged conjugate of β-octaethylporphyrin with methyl pyropheophorbide d was synthesized, the electronic absorption spectrum of which contains bathochromically shifted long-wavelength bands. The resulting compounds could be of interest as potential photosensitizers, sensor dyes and biologically active compounds.

Keywords: Porphyrins, meso-functionalization, electron donors, electron acceptors, azines, electron absorption spectra.

Модификация β−октаэтилпорфирина путем введения амино− и азино−групп в *мезо*−положения

В.Д. Андреева,[a] Г. В. Пономарев,[b] А.О. Шкирдова,[a] В. С. Тюрин,[a@1] И. А. Замилацков[a,c@2]

[a]*Институт физической химии и электрохимии им. А.Н. Фрумкина РАН, 119071 Москва, Российская Федерация*
[b]*Институт биомедицинской химии им. В.Н. Ореховича РАМН, 119121 Москва, Российская Федерация*
[c]*Российский государственный университет им. А.Н. Косыгина, кафедра органической химии, 119071 Москва, Российская Федерация*
[@1]*E-mail: vst-1970@mail.ru*
[@2]*E-mail: joz@mail.ru*

Функционализация β-октаэтилпорфирина была осуществлена путем введения различных амино- и азино-групп в мезо-положения. В качестве донорных заместителей были использованы амино, н-пропиламино, и трифторметилацетиламино группы, в то время как азино-группа была введена в качестве акцептора электронов. Азиновый фрагмент вводили путем формилирования с последующей реакцией с гидразином и затем с ароматическими альдегидами, при этом были получены соответствующие азиновые производные п-нитрофенилбензальдегида и метилового эфира пирофеофорбида d. Было установлено, что в условиях формилирования мезо-(трифторацетамидо)-β-октаэтилпорфирина происходит частичное окисление амидного фрагмента с образованием гидроксамовой кислоты. В результате замещения мезо-положений β-октаэтилпорфирина были получены новые функционализированные порфириновые производные, обладаю-

щие существенно измененными электронно-оптическими свойствами. В частности, был получен конъюгат β-октаэтилпорфирина с метиловым эфиром пирофеофорбида d с азиновым мостиковым фрагментом, электронный спектр поглощения которого содержит батохромно смещенные длинноволновые полосы. Полученные соединения могут представлять интерес в качестве потенциальных фотосенсибилизаторов, сенсорных красителей и биологически активных соединений.

Ключевые слова: Порфирины, мезо-функционализация, доноры электронов, акцепторы электронов, азины, электронный спектр поглощения.

Introduction

Porphyrins are a unique type of dyes whose electron optical properties can be easily tuned by introducing various substituents affecting the aromatic π-electron system of the tetrapyrrole macrocycle. As a result, porphyrins have found wide application in diverse fields as follows. Porphyrin derivatives are used as sensor dyes,[1] including in bioanalysis,[2,3] photosensitizers in medicine,[4–6] photocatalysis[7–10] and photovoltaics.[11–14] The greatest influence on the electronic system of porphyrins is exerted by donor and acceptor substituents at the *meso*-position of the macrocycle.[15] The highest efficiency of the organic dye sensitized solar cells was achieved using photosensitizers based on 5,15-diarylporphyrins substituted with donor and acceptor groups at opposite *meso*-positions.[16] There have been reported a lot of works devoted to studies of similar systems based on synthetic *β*-unsubstituted *meso*-arylporphyrins,[17–21] including bis- and trisporphyrins.[22–26] The effect of the insertion of electron donor and acceptor groups into the *β*-positions of *meso*-tetraarylporphyrins was also investigated.[27–30] At the same time, *β*-substituted porphyrins, as well as those containing no aryl groups in *meso*-positions, have not been sufficiently studied yet. Therefore, in this work, *β*-octaethylporphyrin was selected as a substrate for the functionalization with electron donor amino and electron acceptor azino groups to study their influence on the electron absorption spectra. This synthetic porphyrin is often used as a model of natural porphyrins, in which *β*-positions are fully substituted and, as a rule, there are no *meso*-substituents, except for annulated cycles.

Experimental

General

Reactions were carried out under argon atmosphere using commercially available reagents that were purchased and used as received. Heating reaction vessels was performed with oil bath. Silica gel 40/60 was used for column and flash chromatography. Preparative thin layer chromatography (TLC) was performed using glass plates coated with 5–40 μm silica gel (5 mm thick). ^{1}H and ^{13}C NMR spectra were recorded with a Bruker Avance III 600 MHz spectrometer at 303 K in $CDCl_3$. Chemical shifts are reported relative to signals of residual protons of solvents ($CDCl_3$ – 7.26 ppm). The assignment of the resonances in the ^{1}H and ^{13}C NMR spectra was achieved by the use of DEPT, COSY and HSQC techniques. The LDI-TOF mass spectra were obtained on a Ultraflex-II mass spectrometer (Bruker Daltonics) in a positive ion mode using reflection mode (20 mV target voltage) without matrix. Electronic absorption spectra were recorded with U-2900 (Hitachi) spectrophotometer in quartz rectangular cells of 10 mm path length.

Synthesis

β-Octaethylporphyrin (**1**) was obtained by monopyrrole condensation described by Johnson,[31] Ni(II) complex of *β*-octaethylporphyrin was prepared according to procedure described by K. Smith.[32] *meso*-Nitro-*β*-octaethylporphyrin (**2**) was obtained by nitration of *β*-octaethylporphyrin with $NaNO_2$ in trifluoroacetic acid as described by R. Bonnett.[33] Reduction of *meso*-nitro-*β*-octaethylporphyrin with tin dichloride in hydrochloric acid was used to obtain *meso*-amino-*β*-octaethylporphyrin,[34,35] which was converted to Ni(II) complex of *meso*-amino-*β*-octaethylporphyrin (**3**).[34–36]

*Ni(II) 5-(n-propylamino)-2,3,7,8,12,13,17,18-octaethylporphyrin (**4**).* 0.4 mL of glacial acetic acid and 1.3 mL of 1-propanal (18.2 mmol) were added to a solution of 55 mg (0.091 mmol) of *meso*-amino-*β*-octaethylporphyrin (**3**) in 15 mL of 1,2-dichloroethane. The reaction mixture was stirred for an hour at room temperature, then 1.14 g (18.2 mmol) of $NaBH_3CN$ was added to the solution and the mixture was stirred for another 4 hours. Then the mixture was washed with saturated $NaHCO_3$ (2×30 mL) and water (3×30 mL), dried over anhydrous sodium sulfate and evaporated in vacuum. The residue was purified by the column chromatography with eluent CH_2Cl_2 - *n*-hexane - triethylamine (3 : 5 : 0.01) yielding 41.9 mg (71 %) of the compound **4** (R_f = 0.58). ^{1}H NMR (600 MHz, $CDCl_3$, 303 K) δ ppm: 0.61 (3H, t, $NHCH_2CH_2CH_3$), 1.22 (2H, m, $NHCH_2CH_2CH_3$) 1.68 (6H, t, and CH_2CH_3), 1.75 (18H, m, CH_2CH_3), 3.15 (2H, m, $NHCH_2CH_2CH_3$), 3.73 (12H, m, CH_2CH_3), 3.84 (4H, m, CH_2CH_3), 4.94 (1H, t, $NHCH_2CH_2CH_3$), 9.07 (1H, s, 15-CH), 9.16 (2H, s, 10, 20-CH). UV-Vis (CH_2Cl_2) λ_{max} (A_{rel}) nm: 419 (0.37), 457 (1.00), 546 (0.19). LDI TOF *m/z*: found 648.55, calc. for $[M+H]^+$ $C_{39}H_{52}N_5Ni$ 648.36.

*Ni(II) 5-((trifluoromethylacetyl)amino)-2,3,7,8,12,13,17,18-octaethylporphyrin (**5**).* A solution of 20 mg (0.033 mmol) of *meso*-amino-*β*-octaethylporphyrin (**3**) in 5 mL of CH_2Cl_2 and 184 μL (1.32 mmol) of triethylamine was cooled to 0 °C, and 11 μL (0.073 mmol) of trifluoroacetic acid anhydride was added. The reaction mixture was stirred for 8 h at room temperature, then it was washed with water (5×20mL), dried over anhydrous sodium sulfate and evaporated in vacuum. The residue was purified by the column chromatography with eluent CH_2Cl_2 - *n*-hexane (1 : 1) yielding 15 mg (65 %) of the compound **5** (R_f = 0.55). ^{1}H NMR (600 MHz, $CDCl_3$, 303 K) δ ppm: 1.77 (24H, m, CH_2CH_3), 3.86 (16H, m, CH_2CH_3), 9.56 (3H, m, 10, 15, 20-CH), 9.90 (1H, s, NH). UV-Vis (CH_2Cl_2) λ_{max} (A_{rel}) nm: 400 (1.00), 526 (0.06), 563 (0.13). LDI TOF *m/z*: found 702.48, calc. for $[M+H]^+$ $C_{38}H_{45}F_3N_5NiO$ 702.29.

General procedure of insertion of azine group into Ni(II) β-octaethylporphyrin. Ni(II) 5-((trifluoromethylacetyl)amino)-2,3,7,8,12,13,17,18-octaethylporphyrin (**5**) (40 mg, 0.057 mmol) was dissolved in 15 mL of CH_2Cl_2, then Vilsmeier reagent (freshly prepared from DMF (0.7 mL, 9.06 mmol) and $POCl_3$ (0.7 mL, 7.51 mmol)) was added dropwise to the solution, and the reaction mixture was stirred for 1 hour at reflux. Then

the reaction mixture was washed with water (3×30 mL) to neutral p*H* and 0.5 mL of hydrazine hydrate (98 %, aq.) was added dropwise till the change of the color. The resulting solution was washed with water (3×30 mL) and dried over sodium sulfate and evaporated in vacuum. The residue was purified using preparative TLC with eluent CH_2Cl_2: EtOH = 100: 4 yielding 24 mg (58 %) of the crude hydrazone, which was dissolved in 20 mL of CH_2Cl_2, and 15 mg (0.1 mmol) of *p*-nitrobenzaldehyde was added. The reaction mixture was stirred for 96 hours at reflux, then the solvent was evaporated in vacuum and purified by preparative TLC, eluting with CH_2Cl_2, and yielding 13 mg (26 %) of compound **6** (R_f = 0.51), 8 mg (16 %) of compound **7** (R_f = 0.39) and 4 mg (8 %) of compound **8** (R_f = 0.18).

*Ni(II) (1E,2E)-1-((15-(trifluoroacetylamino)-2,3,7,8,12,13,17,18-octaethylporphyrin-5-yl)methylene)-2-(4-nitrobenzylidene) hydrazine (**6**).* ^{1}H NMR (600 MHz, $CDCl_3$, 303 K) δ ppm: 1.65 (24H, m, CH_2CH_3), 3.75 (16H, m, CH_2CH_3), 8.02 (2H, m, C_6H_4), 8.31 (2H, m, C_6H_4), 8.46 (1H, s, C_6H_4CH=N), 9.23 (2H, m, 10, 20-CH), 9.73 (s, 1 H, NH), 10.75 (1H, s, 15^1-CH=N). UV-Vis (CH_2Cl_2) λ_{max} (A_{rel}) nm: 410 (1.00), 483 (0.18), 540 (0.02), 579 (0.07). LDI TOF *m/z*: found 877.62, calc. for $[M+H]^+$ $C_{46}H_{50}F_3N_8NiO_3$ 877.33.

*Ni(II) (1E,2E)-1-((10-(N-trifluoroacetyl(hydroxylamino))-2,3,7,8,12,13,17,18-octaethylporphyrin-5-yl)methylene)-2-(4-nitrobenzylidene)hydrazine (**7**).* ^{1}H NMR (600 MHz, $CDCl_3$, 303 K) δ ppm: 1.63 (6H, m, CH_2CH_3), 1.73 (18H, m, CH_2CH_3), 3.75 (16H, m, CH_2CH_3), 8.01 (2H, m, C_6H_4), 8.30 (2H, m, C_6H_4), 8.44 (1H, s, C_6H_4CH=N), 9.21 (2H, m, 15, 20-CH), 10.80 (1H, s, 5^1-CH=N). UV-Vis (CH_2Cl_2) λ_{max} (A_{rel}) nm: 410 (1.00), 504 (0.41), 578 (0.06), 653 (0.08). LDI TOF *m/z*: found 893.62, calc. for $[M+H]^+$ $C_{46}H_{50}F_3N_8NiO_4$ 893.33.

*Ni(II) (1E,2E)-1-((15-(N-trifluoroacetyl(hydroxylamino))-2,3,7,8,12,13,17,18-octaethylporphyrin-5-yl)methylene)-2-(4-nitrobenzylidene)hydrazine (**8**).* ^{1}H NMR (600 MHz, $CDCl_3$, 303 K) δ ppm: 1.70 (24H, m, CH_2CH_3), 3.71 (16H, m, CH_2CH_3), 8.04 (2H, m, C_6H_4), 8.31 (2H, m, C_6H_4), 8.48 (1H, s, C_6H_4CH=N), 9.21 (2H, s, 10, 20-CH), 10.78 (1H, s, 5^1-C*H*=N). UV-Vis (CH_2Cl_2) λ_{max} (A_{rel}) nm: 412 (1.00), 488 (0.27), 544 (0.05), 581 (0.03), 625 (0.02). LDI TOF *m/z*: found 893.62, calc. for $[M+H]^+$ $C_{46}H_{50}F_3N_8NiO_4$ 893.33.

*(1E,2E)-1-(methylpyropheophorbide-d-3^1-ylidene)-2-((2,3,7,8,12,13,17,18-octaethylporphyrinatonickel-5-yl)methylene) hydrazine (**9**).* R_f = 0.33 (CH_2Cl_2 / EtOH = 100 : 1). Yield: 4 mg (18 %) from 20 mg (0.029 mmol) of **5** and 14 mg (0.025 mmol) of methyl pyropheophorbide *d*. ^{1}H NMR (600 MHz, $CDCl_3$, 303 K) δ ppm: 11.31 (1H, m, CH=N (NiOEP), 10.55 (1H, m, CH=N (PPPd)), 9.82 (1H, m, 5-CH (PPPd)), 9.58 (1H, s, 10-CH (PPPd), 9.28 (2H, m, 10, 20-CH (NiOEP)), 8.67 (1H, m, 20-CH, PPPd), 8.12 (1H, s, NHCOCF$_3$), 5.33 (1H, d, *J* = 19.4 Hz, 13^2-CH^a), 5.17 (1H, d, *J* = 19.4 Hz, 13^2-CH^b), 4.53 (1H, m, 18-CH), 4.35 (1H, m, 17-CH), 3.84 (21H, m, CH_2CH_3 (NiOEP), 8^1-CH_2, 12-CH_3 (PPPd)), 3.65 (3H, m, 17^2-CO_2CH_3), 3.57 (3H, m, 2-CH_3), 3.43 (3H, m, 7-CH_3), 2.75 (1H, m, 17^1-H^a), 2.60 (1H, m, 17^2-H^a), 2.39 (2H, m, 17^1-H^b, 17^2-H^b), 1.84 (27H, m, CH_2CH_3 (NiOEP), 18-CH_3 (PPPd)), 1.79 (3H, t, J = 7.16 Hz, 8^2-CH_3), –1.70 (2H, s, NH (PPPd)). UV-Vis (CH_2Cl_2) λ_{max} (A_{rel}) nm: 387 (0.38), 424 (0.96), 440 (0.93), 522 (0.12), 554 (0.17), 630 (0.07), 693 (1.00). LDI TOF *m/z*: found 1276.73, calc. for $[M+H]^+$ $C_{72}H_{79}F_3N_{11}NiO_4$ 1276.56.

Results and Discussion

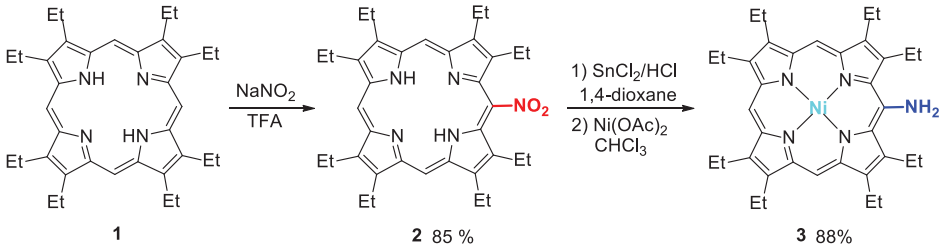
Primary functionalization of β*-octaethylporphyrin*

The free *meso*-positions of β-octaethylporphyrin (OEP) have an increased reactivity and easily react with electrophiles in electrophilic substitution reactions. The primary functionalization of OEP (**1**) was carried out by electrophilic nitration with sodium nitrite in trifluoroacetic acid.[37] The obtained *meso*-nitro-β-octaethylporphyrin (**2**) was then subjected to the reduction of the nitro group with tin dichloride in hydrochloric acid yielding the *meso*-amino-β-octaethylporphyrin[36] which was metalated to the corresponding nickel complex **3** [34] (Scheme 1).

Transformation of the meso-amino-group of β*-octaethylporphyrin*

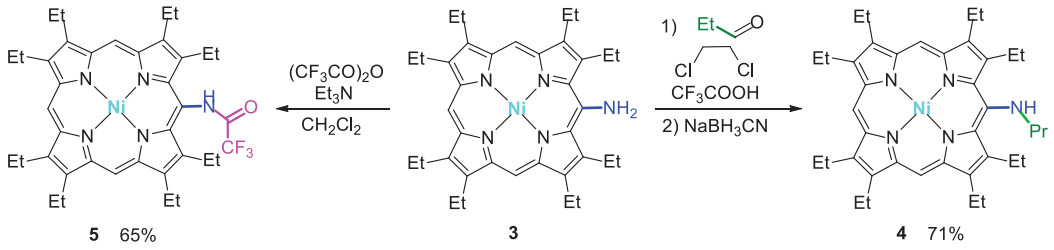
The *meso*-amino-group of β-octaethylporphyrin was subjected to the further transformations. First, the alkylation of the primary amino-group was carried out *via* one-pot two stage process: treatment of **3** with propanal in 1,2-dichloroethane containing trifluoroacetic acid as a catalyst led to the formation of the imino-group which was then reduced with sodium cyanoborohydride yielding *n*-propylamino substituted porphyrin **4** with 71 % yield. Alternatively, the acylation of the amino group was performed with trifluoroacetic anhydride and triethylamine in dichloromethane, resulting in the corresponding *meso*-trifluoroacetamido-β-octaethylporphyrin **5** , which was isolated with 65 % yield (Scheme 2).

Emergence of the *meso*-amino group at the porphyrin macrocycle strongly perturbs π-electron system of the aromatic tetrapyrrole macrocycle significantly affecting electron absorption spectrum: the Soret band of the *meso*-amino-β-octaethylporphyrin **3** was shifted for 27 nm towards longer wavelengths, while the Q-bands were broadened with decreasing intensity. The substitution of the hydrogen atom of the *meso*-amino group in **3** with a propyl group led to the even larger bathochromic shift of the main absorption band from 418 nm to 457 nm in **4** (Figure 1). An additional band at 416 nm appeared in the spectrum of **4**. The trifluoroacylation of the amino group decreased its donor ability and the spectrum of the acylated product **5** nearly approached that of NiOEP, but all the bands remained



1 **2** 85 % **3** 88%

Scheme 1. Primary functionalization of β-octaethylporphyrin.



Scheme 2. Transformations of the amino group of the *meso*-amino-β-octaethylporphyrin.

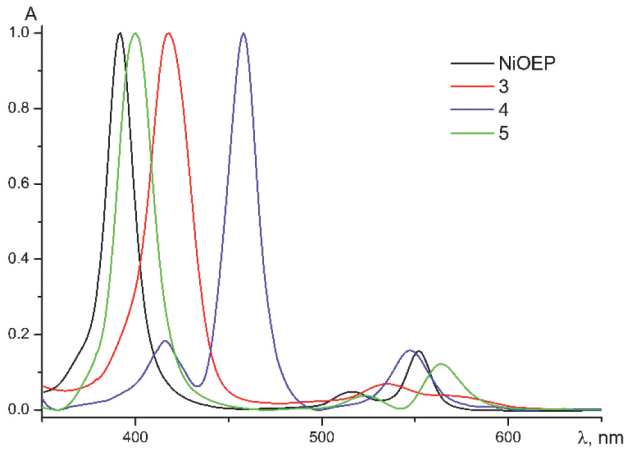


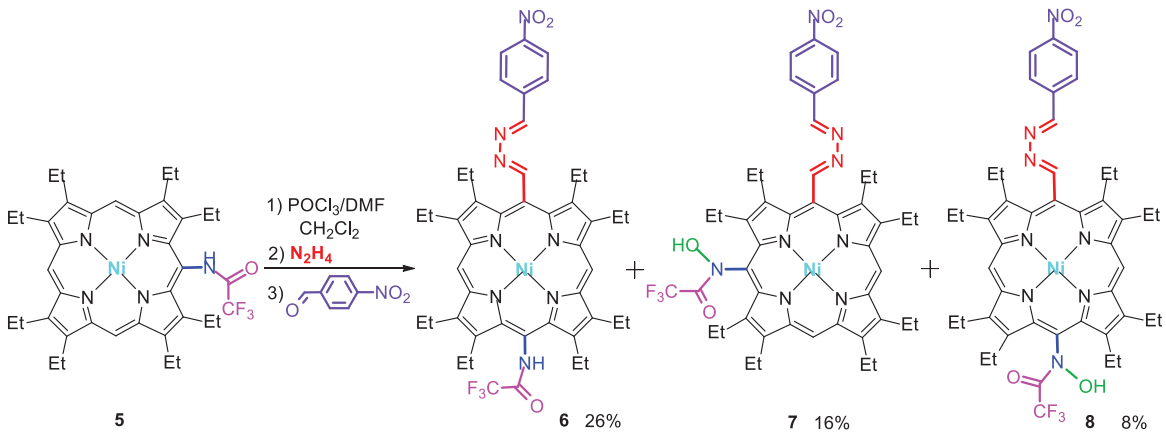
Figure 1. UV-Vis absorption spectra of Ni(II) β-octaethylporphyrin (NiOEP) and the corresponding *meso*-amino-derivatives **3**–**5**. Spectra were recorded in CH_2Cl_2 at concentration of 10^{-5} M.

bathochromically shifted for approximately 10 nm. The Q-bands were generally less affected by the *meso*-amino groups compared to the Soret bands.

Synthesis of azines

The electron acceptor groups were planned to be inserted at the opposite to the amino-substituent *meso*-position in order to create push-pull type substitution pattern. Strong influence on the π-electron system can be exerted with electron acceptor possessing an extented π-conjugated system, and an arylazine substituent can be regarded as such. Previously, aryl azines of porphyrinoids have been synthesized by the condensation of tetrapyrrole hydrazones and arylaldehydes.[38] In turn, hydrazones have been obtained *via* formylation followed by the reaction of the formylporphyrins with hydrazine.[39] The trifluoroacylated amino derivative **5** was used as a starting material for the electron acceptor fragment insertion as the trifluoroacyl played a role of a protective group for the reactive amino group. The Vilsmeier-Haack formylation of **5** with $POCl_3$/DMF[39–41] was initially performed, and the so called intermediate "phosphorus complex" was then subjected to the reaction with hydrazine leading to the hydrazone, which was used in the next step without isolation. Finally, *p*-nitrobenzaldehyde was added to the reaction mixture containing the hydrazone and the condensation products of the three stage reaction were isolated. The main product **6** was the target *p*-nitrobenzalazine of the 5-(trifluoroacetylamino)-10-formylporphyrin isolated with 26 % yield. Two additional products were formed, which were determined to be isomeric hydroxamic acids **7** and **8** with 8 % and 16 % yields, respectively (Scheme 3).

To the best of our knowledge, the transformation of amido group into hydroxamic acid derivative was observed for the first time without an oxidant, during the Vilsmeier-Haack formylation reaction. An oxidation of the amide to the hydroxamic acid possibly took place upon the action of the formylating complex $POCl_3$/DMF. That



Scheme 3. Synthesis of *meso*-disubsituted β-octaethylporphyrin derivatives.

supports the fact of the formation of the mixture of 5,10- and 5,15-substituted porphyrin isomers of the hydroxamic acid **7**, **8**, while only the 5,15-substituted amide product **6** was formed. Weak but still donor amide group of **5** directs an electrophile to the opposite *meso*-position during the formylation reaction, leading to **6**. However, a side reaction produced a partial transformation of **5** into an intermediate hydroxamic acid derivative, and since the hydroxamic group was practically not an electron donor, the formylating electrophile could attack any *meso* position, leading to a statistical distribution of the 5,10- and 5,15-products **7** and **8**, respectively.

Upon insertion of the azine substituent into **5** a new intense band at 483 nm has emerged in **6** and the slight bathochromic shift of the Soret band for 11 nm and 16 nm shift of Q-bands were observed (Figure 2). Comparing spectra of **6** and similar azine derivative of NiOEP and *p*-nitrobenzaldehyde (NiOEPCHNNCHC$_6$H$_4$NO$_2$)[38] but without *meso*-amido substituent, one can see that the spectrum of **6** is bathochromically shifted relatively that of NiOEPCHNNCHC$_6$H$_4$NO$_2$, and Q-bands are of relatively higher intensity. These differences are due to the influence of *meso*-trifluoroacetamido group. The main Soret and Q-bands of NiOEPCHNNCHC$_6$H$_4$NO$_2$ are very close in position to that of **5**, though being of less intensity. Thus, the insertion of *meso*-trifluoroacetamido or the *p*-nitrobenzalazine group led to the almost identical bathochromic shifts of the main porphyrin absorption bands. However, azine group insertion led to the emergence of the additional band near 480 nm. Cooperative influence of both azine and amido groups additively shifted all the bands and notably increased the intensity of the 480 nm band. Hydroxamic acid derivative **8**, which is similar to **6**, possesses slightly different spectrum, which contains a new long wavelength band at 641 nm. The spectrum of 5,10-isomer of the hydroxamic acid derivative **7** is considerably different: a quite strong band at 504 nm and the longest wavelength band at 653 nm with appreciable intensity.

Further expansion of the π-electron system of the azine functionalized disubstituted β-octaethylporphyrin was achieved through the conjugation with another tetrapyrrole. Again, the same three step synthetic scheme was applied: formylation of **5** followed by treatment with hydrazine led to the hydrazone formation which was then reacted with methyl pyropheophorbide *d* (PPPd), containing formyl group at β-position of the tetrapyrrole ring resulting in formation of the azine bridged porphyrin-chlorin conjugate **9** with 18 % yield. In comparison with the reaction

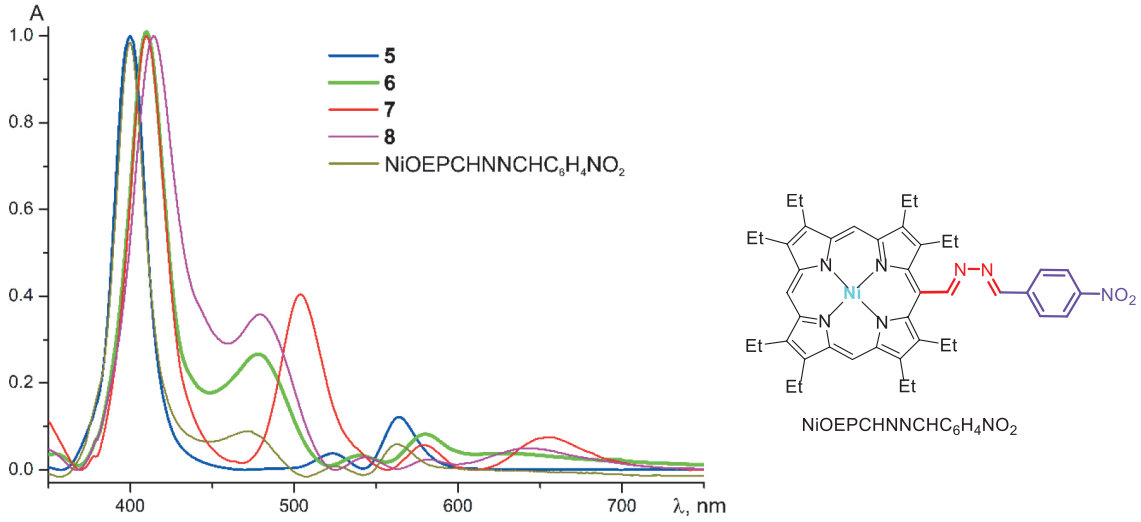
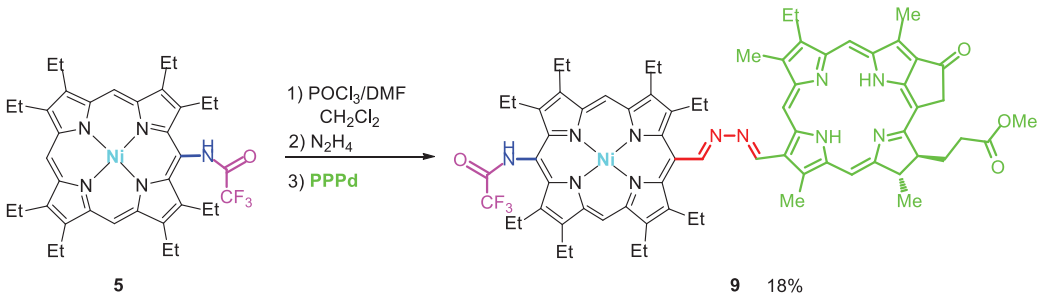


Figure 2. UV-Vis absorption spectra of trifluoroacylated amino derivative **5** and their azine derivatives **6**–**8**, and *p*-nitrobenzalazine derivative of *meso*-formyl-β-octaethylporphyrin (NiOEPCHNNCHC$_6$H$_4$NO$_2$)[38] for comparison. The spectra were recorded in CH_2Cl_2 at concentration of 10^{-5} M.



Scheme 4. Synthesis of the azine bridged conjugate **9** of *meso*-(trifluoroacetamido)-β-octaethylporphyrin with methyl pyropheophorbide-*d* (PPPd).

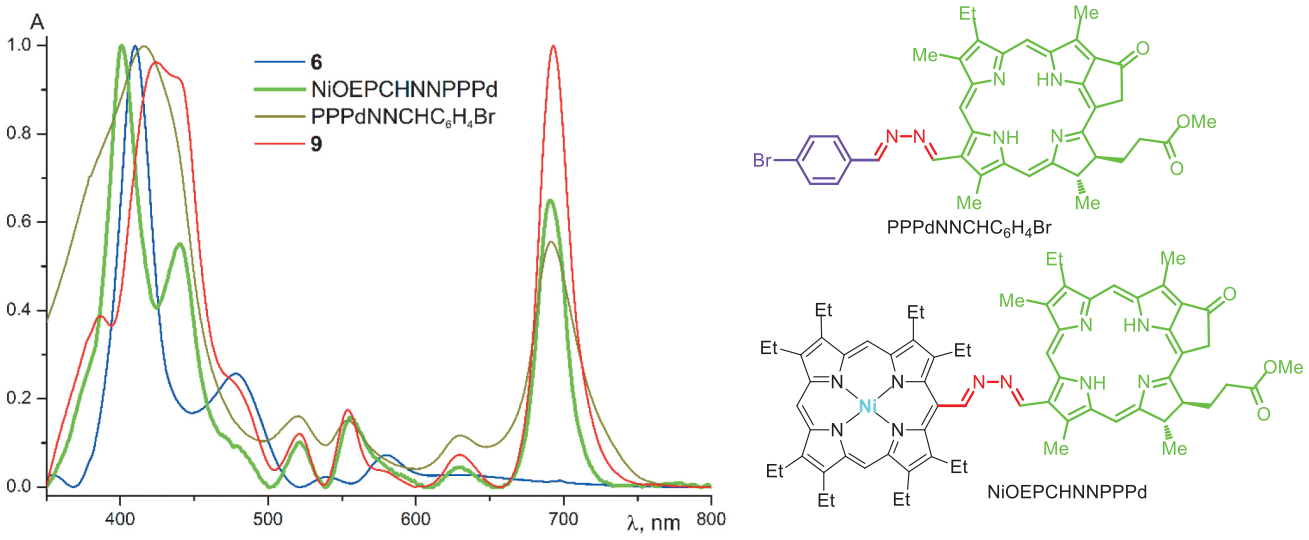


Figure 3. UV-Vis absorption spectra of trifluoroacetamido *p*-nitrobenzalazine derivative **6**, azine bridged conjugate of trifluoroacetamido substituted NiOEP and PPPd **9**, azine bridged conjugate of NiOEP and PPPd (NiOEPCHNNPPPPd)[38] and *p*-bromobenzalazine derivative of methyl pyropheophorbide *d* (PPPdNNCHC$_6$H$_4$Br)[38] for comparison. Spectra were recorded in CH_2Cl_2 at concentration of 10^{-5} M.

with *p*-nitrobenzaldehyde, which was used in 3-fold excess, considerably more valuable methyl pyropheophorbide *d* was used in the less excess of 1.5 eq., and this fact was possibly a cause of the lower yield.

The electron absorption spectrum of the azine bridged porphyrin-chlorin conjugate **9** significantly differs from that of the *p*-nitrobenzalazine derivative **6** due to presence of the chlorin chromophore (Figure 3). For comparison, the spectra of the *p*-bromobenzalazine derivative of methyl pyropheophorbide *d* (PPPdNNCHC$_6$H$_4$Br) and the azine bridged conjugate of NiOEP and PPPd (NiOEPCHNNPPPPd) were shown.[38] Spectra of all azines of PPPd contain broad Soret band which is resolved in two bands in the case of NiOEPCHNNPPPPd. The Soret band of the conjugate **9** is red-shifted for 23 nm compared to the NiOEPCHNNPPPPd which can be attributed to the influence of the *meso*-trifluoroacetamido substituent. All long wavelength bands are very similar for all the PPPd azines. The longest wavelength and most intense Q_y-bands, belonged to the chlorin chromophore, do not change in position, but vary their intensity in parallel with the π-conjugation chain length. The least intensity was observed for PPPdNNCHC$_6$H$_4$Br, and compound **9** with the most expanded π-conjugation possessed the Q_y-band of even higher intensity than the Soret band.

Conclusions

The *meso*-functionalization of Ni(II) *β*-octaethylporphyrin was readily performed basing on the electrophilic substitution reactions (nitration and formylation) followed by nucleophilic addition, substitution as well as reduction. Unprecedented oxidation of the amide functionality was observed during the formylation process, which led to formation of hydroxamic acid derivatives of the porphyrin. *meso*-Substitution significantly altered electron absorption spectra of the porphyrin chromophore. *meso*-Propylamine group causes bathochromic shift of the Soret band for almost 40 nm. Insertion of two *meso*-substituents led even to greater spectral changes. Combination of trifluoroacetamido and arylazine groups strongly increased the absorption near 500 nm and considerably shifted the Q-band maxima to the red region up to 650 nm. The azine bridged conjugation of *meso*-trifluoroacetamido-*β*-octaethylporphyrin with methyl pyropheophorbide *d* led to the substantial growth of the Q-band intensity as well as red-shifting Soret band. Thus, the *meso*-substitution with the electron donor and acceptor groups can be regarded as a powerful methodology of tuning the optical spectral properties of tetrapyrrole dyes. The resulting compounds could be of interest as potential photosensitizers, sensor dyes and biologically active compounds.

Acknowledgements. The reported study was funded by the Ministry of science and higher education of Russian federation, agreement No 075-15-2021-983.

References

1. Paolesse R., Nardis S., Monti D., Stefanelli M., Di Natale C. *Chem. Rev.* **2017**, *117*, 2517–2583, DOI: 10.1021/acs.chemrev.6b00361.
2. Papkovsky D.B., O'Riordan T.C. *J. Fluoresc.* **2005**, *15*, 569–584, DOI: 10.1007/s10895-005-2830-x.
3. Norvaiša K., Kielmann M., Senge M.O. *ChemBioChem* **2020**, *21*, 1793–1807, DOI: 10.1002/cbic.202000067.
4. Sternberg E.D., Dolphin D., Brückner C. *Tetrahedron* **1998**, *54*, 4151–4202, DOI: 10.1016/S0040-4020(98)00015-5.
5. Glowacka-Sobotta A., Wrotynski M., Kryjewski M., Sobotta L., Mielcarek J. *J. Porphyrins Phthalocyanines* **2019**, *23*, 1–10, DOI: 10.1142/s108842461850116x.
6. Ethirajan M., Chen Y., Joshi P., Pandey R.K. *Chem. Soc. Rev.* **2011**, *40*, 340–362, DOI: 10.1039/b915149b.
7. Zheng Y., Wang J., Zhang J., Peng T., Li R. *Dalton Trans.* **2017**, *46*, 8219–8228, DOI: 10.1039/c7dt01029j.
8. Zuo Q., Cheng G., Luo W. *Dalton Trans.* **2017**, *46*, 9344–9348, DOI: 10.1039/c7dt01694h.

9. Barona Castano J., Carmona-Vargas C., Brocksom T., Oliveira K. *Molecules* **2016**, *21*, 310, DOI: 10.3390/molecules21030310.
10. Manbeck G.F., Fujita E. *J. Porphyrins Phthalocyanines* **2015**, *19*, 45–64, DOI: 10.1142/s1088424615300013.
11. Mathew S., Yella A., Gao P., Humphry-Baker R., Curchod B.F.E., Ashari-Astani N., Tavernelli I., Rothlisberger U., Nazeeruddin M.K., Graetzel M. *Nat. Chem.* **2014**, *6*, 242–247, DOI: 10.1038/nchem.1861.
12. Panda M.K., Ladomenou K., Coutsolelos A.G. *Coord. Chem. Rev.* **2012**, *256*, 2601–2627, DOI: 10.1016/j.ccr.2012.04.041.
13. Krishna J.V.S., Mrinalini M., Prasanthkumar S., Giribabu L. In: *Dye-Sensitized Solar Cells* (Soroush M., Lau K.K.S., Eds.), Academic Press: **2019**; p. 231–284, DOI: 10.1016/B978-0-12-814541-8.00007-0.
14. Diau E.W.-G., Li L.-L. In: *Handbook of Porphyrin Science*, World Scientific Publishing Co. Pte. Ltd., **2014**, *Vol. 28*, p. 279–317.
15. Urbani M., Grätzel M., Nazeeruddin M.K., Torres T. *Chem. Rev.* **2014,** *114*, 12330–12396, DOI: 10.1021/cr5001964.
16. Yella A., Lee H.-W., Tsao H.N., Yi C., Chandiran A.K., Nazeeruddin M.K., Diau E.W.-G., Yeh C.-Y., Zakeeruddin S.M., Grätzel M. *Science* **2011**, *334*, 629–634, DOI: 10.1126/science.1209688.
17. Santhanamoorthi N., Lo C.-M., Jiang J.-C. *J. Phys. Chem. Lett.* **2013**, *4*, 524–530, DOI: 10.1021/jz302101j.
18. Ornso K.B., Garcia-Lastra J.M., Thygesen K.S. *Phys. Chem. Chem. Phys.* **2013**, *15*, 19478–19486, DOI: 10.1039/c3cp54050b.
19. Kang S.H., Choi I.T., Kang M.S., Eom Y.K., Ju M.J., Hong J.Y., Kang H.S., Kim H.K. *J. Mater. Chem. A* **2013**, *1*, 3977–3982, DOI: 10.1039/c3ta01128c.
20. Ishida M., Hwang D., Koo Y.B., Sung J., Kim D.Y., Sessler J.L., Kim D. *Chem. Commun.* **2013**, *49*, 9164–9166, DOI: 10.1039/c3cc44847a.
21. Mathew S., Iijima H., Toude Y., Umeyama T., Matano Y., Ito S., Tkachenko N.V., Lemmetyinen H., Imahori H. *J. Phys. Chem. C* **2011**, 115, 14415–14424, DOI: 10.1021/jp2030208.
22. Liu Y., Lin H., Li J., Dy J.T., Tamaki K., Nakazaki J., Nakayama D., Nishiyama C., Uchida S., Kubo T., Segawa H. *Phys. Chem. Chem. Phys.* **2012**, *14*, 16703–16712, DOI: 10.1039/c2cp43165c.
23. Hamamura T., Dy J.T., Tamaki K., Nakazaki J., Uchida S., Kubo T., Segawa H. *Phys. Chem. Chem. Phys.* **2014**, *16*, 4551–4560, DOI: 10.1039/c3cp55184a.
24. Zervaki G.E., Roy M.S., Panda M.K., Angaridis P.A., Chrissos E., Sharma G.D., Coutsolelos A.G. *Inorg. Chem.* **2013**, *52*, 9813–9825, DOI: 10.1021/ic400774p.
25. Liu Y., Lin H., Dy J.T., Tamaki K., Nakazaki J., Nakayama D., Uchida S., Kubo T., Segawa H. *Chem. Commun.* **2011**, *47*, 4010–4012, DOI: 10.1039/c0cc03306e.
26. Mathew S., Imahori H. In: *Application of Multiporphyrin Arrays to Solar Energy Conversion*; Pan Stanford Publishing Pte. Ltd.: **2012**. p. 439–498, DOI: 10.1201/b11621-10.
27. Imahori H., Umeyama T., Ito S. *Acc. Chem. Res.* **2009**, *42*, 1809–1818, DOI: 10.1021/ar900034t.
28. Chaudhri N., Cong L., Grover N., Shan W., Anshul K., Sankar M., Kadish K.M. *Inorg. Chem.* **2018**, *57*, 13213–13224, DOI: 10.1021/acs.inorgchem.8b01690.
29. Di Carlo G., Caramori S., Trifiletti V., Giannuzzi R., De Marco L., Pizzotti M., Orbelli Biroli A., Tessore F., Argazzi R., Bignozzi C.A. *ACS Applied Materials & Interfaces* **2014**, *6*, 15841–15852, DOI: 10.1021/am503113x.
30. Di Carlo G., Orbelli Biroli A., Pizzotti M., Tessore F., Trifiletti V., Ruffo R., Abbotto A., Amat A., De Angelis F., Mussini P.R. *Chem. Eur. J.* **2013**, *19*, 10723–10740, DOI: 10.1002/chem.201300219.
31. Sessler J.L., Mozaffari A., Johnson M.R. *Org. Synth.* **1992**, *70*, 68–75, DOI: 10.15227/orgsyn.070.0068.
32. Shelnutt J.A., Medforth C.J., Berber M.D., Barkigia K.M., Smith K.M. *J. Am. Chem. Soc.* **1991**, *113*, 4077–4087, DOI: 10.1021/ja00011a004.
33. Bonnett R., Stephenson G.F. *J. Org. Chem.* **1965**, *30*, 2791–2798, DOI: 10.1021/jo01019a070.
34. Sprutta N., Rath S.P., Olmstead M.M., Balch A.L. *Inorg. Chem.* **2005**, *44*, 1452–1459, DOI: 10.1021/ic0486623.
35. Crossley M.J., King L.G., Pyke S.M., Tansey C.W. *J. Porphyrins Phthalocyanines* **2002**, *06*, 685–694, DOI: 10.1142/s1088424602000816.
36. Matsumura M., Tanatani A., Kaneko T., Azumaya I., Masu H., Hashizume D., Kagechika H., Muranaka A., Uchiyama M. *Tetrahedron* **2013**, *69*, 10927–10932, DOI: 10.1016/j.tet.2013.10.069.
37. Mikus A., Łopuszyńska B. *Chemistry – An Asian Journal* **2021**, *16*, 261–276, DOI: 10.1002/asia.202000985.
38. Belyaev E.S., Shkirdova A.O., Kozhemyakin G.L., Tyurin V.S., Emets V.V., Grinberg V.A., Cheshkov D.A., Ponomarev G.V., Tafeenko V.A., Radchenko A.S., Kostyukov A.A., Egorov A.E., Kuzmin V.A., Zamilatskov I.A. *Dyes Pigm.* **2021**, *191*, 109354, DOI: 10.1016/j.dyepig.2021.109354.
39. Shkirdova A.O., Zamilatskov I.A., Stanetskaya N.M., Tafeenko V.A., Tyurin V.S., Chernyshev V.V., Ponomarev G.V., Tsivadze A.Y. *Macroheterocycles* **2017**, *10*, 480–486, DOI: 10.6060/mhc171148z.
40. Erzina D.R., Zamilatskov I.A., Stanetskaya N.M., Tyurin V.S., Kozhemyakin G.L., Ponomarev G.V., Chernyshev V.V., Fitch A.N. *Eur. J. Org. Chem.* **2019**, *2019*, 7, 1508–1522, DOI: 10.1002/ejoc.201801659.
41. Tyurin V.S., Erzina D.R., Zamilatskov I.A., Chernyadyev A.Y., Ponomarev G.V., Yashunskiy D.V., Maksimova A.V., Krasnovskiy A.A., Tsivadze A.Y. *Macroheterocycles* **2015**, *8*, 376–383, DOI: 10.6060/mhc151199z.

Received 16.11.2021
Accepted 20.12.2021