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Статья

Benzoannelated A₃B−Phthalocyanines with Diethyleneglycol Substituents: Synthesis and Control of Aggregation

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New benzoannelated phthalocyanine H_2A_3B has been synthesized by cross-condensation of 4,5-dibutoxyphthalonitrile A and naphthalonitrile B bearing two diethyleneglycol substituents. UV-Vis and ¹H NMR measurements performed for H_2A_3B showed that the presence of free OH-groups in H_2A_3B enhances its aggregation in solution in comparison with its O-tetrahydropyranyl derivative H_2A_3Bt, which can be considered as a way to control the physicochemical properties of asymmetric phthalocyanines.

Keywords: Benzoannelated phthalocyanine, UV-Vis spectroscopy, NMR spectroscopy, aggregation.

Бензоаннелированные фталоцианины А₃В−типа с диэтиленгликолевыми заместителями: синтез и контроль агрегации

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Новый бензоаннелированный фталоцианин H_2A_3B был синтезирован путем кросс-конденсации 4,5-дибутокси-фталонитрила A и нафталонитрила B с двумя диэтиленгликолевыми заместителями. Исследования методами ЭСП и ¹Н ЯМР, проведенные для H_2A_3B, показали, что наличие свободных ОН-групп в H_2A_3B усиливает агрегацию этого фталоцианина в растворе по сравнению с О-тетрагидропиранильным производным H_2A_3Bt, что можно рассматривать как способ управления физико-химическими свойствами несимметричных фтало-цианинов.

Ключевые слова: Бензоаннелированные фталоцианины, электронная спектроскопия поглощения, спектроско-пия ЯМР, агрегация.

Introduction

One of the important trends in modern science is the search for approaches to obtaining functional hybrid organic-inorganic materials for the development of molecular electronics elements and other topical applications, such as nonlinear optics, sensors and catalysis.[1] In the development of such hybrid materials, oxides, metal nanoparticles and quantum dots, etc., are used as inorganic substrates, and macrocyclic compounds are often used as the organic component, among which phthalocyanines attract particular attention.[2–5] For example, the immobilization of phthalo-cyanines on the surface of quantum dots and nanoparticles leads to conjugates with improved nonlinear optical properties affording their application as optical limiters of laser radiation.[6,7]

Compared with the widely studied symmetrical phthalocyanines, the information about asymmetrical analogues is limited.[8,9] At the same time, from the viewpoint of phthalocyanines immobilization on the surface of inorganic materials, asymmetric phthalocyanines are particularly interesting, because the introduction of various types of functional fragments and simultaneously anchoring groups for molecule attachment makes it possible to extend the applications of hybrid materials based on them. From this viewpoint, terminal OH-groups are particularly attractive due to wide possibilities of their post-synthetic modification to obtain anchoring groups with desired functionalities.[10–12]

Here we report on synthesis and characterization of novel benzoannelated phthalocyanine **H₂A₃B** obtained from 4,5-dibutoxyphthalonitrile **A** and naphthalonitrile **B** with two diethyleneglycol substituents bearing two terminal OH-groups. Further conversion of these OH groups into tetrahydropyranyl derivatives afforded the protected ligand **H₂A₃Bt** which had markedly lower tendency to aggregation in comparison with the staring **H₂A₃B** molecule.

Experimental

The starting precursors 4,5-di-*n*-butoxyphthalonitrile **A**[13] and 6,7-bis[2'-(2''-hydroxyethoxy)ethoxy]-2,3-naphthalonitrile **B**[14] were synthesized according to previously reported procedures. Chloroform (puriss) was dried over $CaCl_2$ and distilled over K_2CO_3. Pentanol (Aldrich) was distilled over Mg and stored under argon. All other reagents were used without purification as received from commercial suppliers. Column chromatography was performed on neutral alumina (Macherey-Nagel) and BioBeads S-X1 (BioRad).

Mass spectral data were acquired on Bruker Daltonics Ultraflex spectrometer with 2,4-dihydroxybenzoic acid as the matrix. Mass spectrometer operated in a positive ion mode using an *m/z* range of 500–5000 amu. NMR spectra were recorded with Bruker Avance 600 spectrometer. NMR spectra were referenced against the residual solvent signal. Deuterated chloroform was filtered through the layer of dry neutral alumina prior the preparation of samples. Ground state electronic absorption was measured on Jasco V770 spectrophotometer in quartz cells with 1, 2, 5 and 10 mm optical pathways.

Phthalocyanine H₂A₃B: A mixture of phthalonitrile **A** (431 mg; 1.6 mmol), naphthalonitrile **B** (122 mg; 0.32 mmol), and magnesium (91 mg; 3.84 mmol) was suspended in 13 mL of 1-pentanol and mixture was degassed and refluxed under argon atmosphere for 16 h. After that, reaction mixture was cooled to 100 °C, mixture of 1.5 mL CF_3COOH and 1.5 mL of water was added to produce metal-free ligand. The progress of demetalation was monitored by UV-Vis spectra. After 15 minutes demetallation was complete and dark-green reaction mixture was sonicated with the mixture of water and EtOH (6:4 v/v), the precipitate was filtered, washed with aqueous EtOH, washed off the filter with $CHCl_3$ and MeOH mixture and the filtrate was evaporated. The resulting mixture of metal-free complexes was separated *via* column chromatography on neutral alumina. Symmetrical phthalocyanine **H₂A₄** was eluted with $CHCl_3$ + 20 vol.% hexane, and target low-symmetry phthalocyanine **H₂A₃B** was eluted with the mixture of $CHCl_3$ + 5 vol.% MeOH followed by size-exclusion chromatography in BioBeads S-X1 (elution with the mixture of $CHCl_3$ + 2.5 vol.% MeOH). Green solid, yield 90 mg (16 %). MALDI TOF MS, *m/z*: calculated for $C_{68}H_{84}N_8O_{12}$ – 1205.5, found 1204.7 – $[M]^+$. ¹H NMR (CDCl₃, 303 K) δ$_H$ ppm: 7.87, 7.71 and 7.33 (3s, 3×2H, 3H$_{Pc}$), 6.88 (s, 2H, 1,4-H$_N$), 6.23 (s, 2H, 5,8-

H$_N$), 4.40–3.81 (m, 30H, 1-OCH₂ + α,β,γ,δ-OCH₂ + OH), 4.36–3.81 (m, 24H, 2,3-CH₂), 1.29–1.23 (m, 18H, CH₃), –3.59 (s, 2H, NH). UV-Vis (CHCl₃) λ_{max} (lgε) nm: 729 (5.17), 684 (5.11), 616 (4.47), 409 (4.60), 345 (4.97), 303 (4.73).

Phthalocyanine H₂A₃Bt: phthalocyanine **H₂A₃B** (35 mg, 29 μmol) was dissolved in 10 mL of CHCl₃, *p*-toluenesulfonic acid (TsOH, 10 mg) and excess of 3,4-dihyro-2H-pyran (0.15 mL) were added and mixture was stirred at room temperature for 3 h. Upon completion of the reaction evidenced by TLC, the acid was neutralized with 0.5 mL of saturated aqueous solution of Na_2CO_3. The product was purified using a column chromatography on neutral alumina (gradient elution with 10–0 vol.% hexane in chloroform followed by 0–2 vol.% MeOH in chloroform). Yield 37 mg (92 %). MALDI-TOF MS: *m/z* calculated for $C_{78}H_{100}N_8O_{14}$ – 1373.7, found 1374.0 – $[M]^+$. ¹H NMR (CDCl₃, 303 K) δ$_H$ ppm: 8.20 (s, 2H, 1,4-H$_N$), 8.14, 8.07 and 7.98 (3s, 3×2H, 3H$_{Pc}$), 7.23 (s, 2H, 4,8-H$_N$), 4.79–4.74 (m, 2H, OCHO^{THP}), 4.53–4.45 (m, 20H, α,β-OCH₂ + 1-CH₂), 4.21–4.18 (m, 4H, γ-CH₂), 4.08–4.04 (m, 2H, CH^{THP}), 4.01–3.96 (m, 6H, δ-CH₂ + CH^{THP}), 3.82–3.78 (m, 2H, CH^{THP}), 3.57 (m, 2H, CH^{THP}), 2.24–2.15 (m, 12H, 2-CH₂), 1.93–1.79 (m, 16H, 3-CH₂+CH^{THP}), 1.61–1.55 (m, 4H, CH^{THP}), 1.32–1.26 (m, 18H, CH₃), –2.89 (s, 2H, NH). UV-Vis (CHCl₃) λ_{max} (lgε) nm: 731 (5.12), 685 (5.08), 617 (4.50), 409 (4.58), 345 (4.95), 304 (4.68).
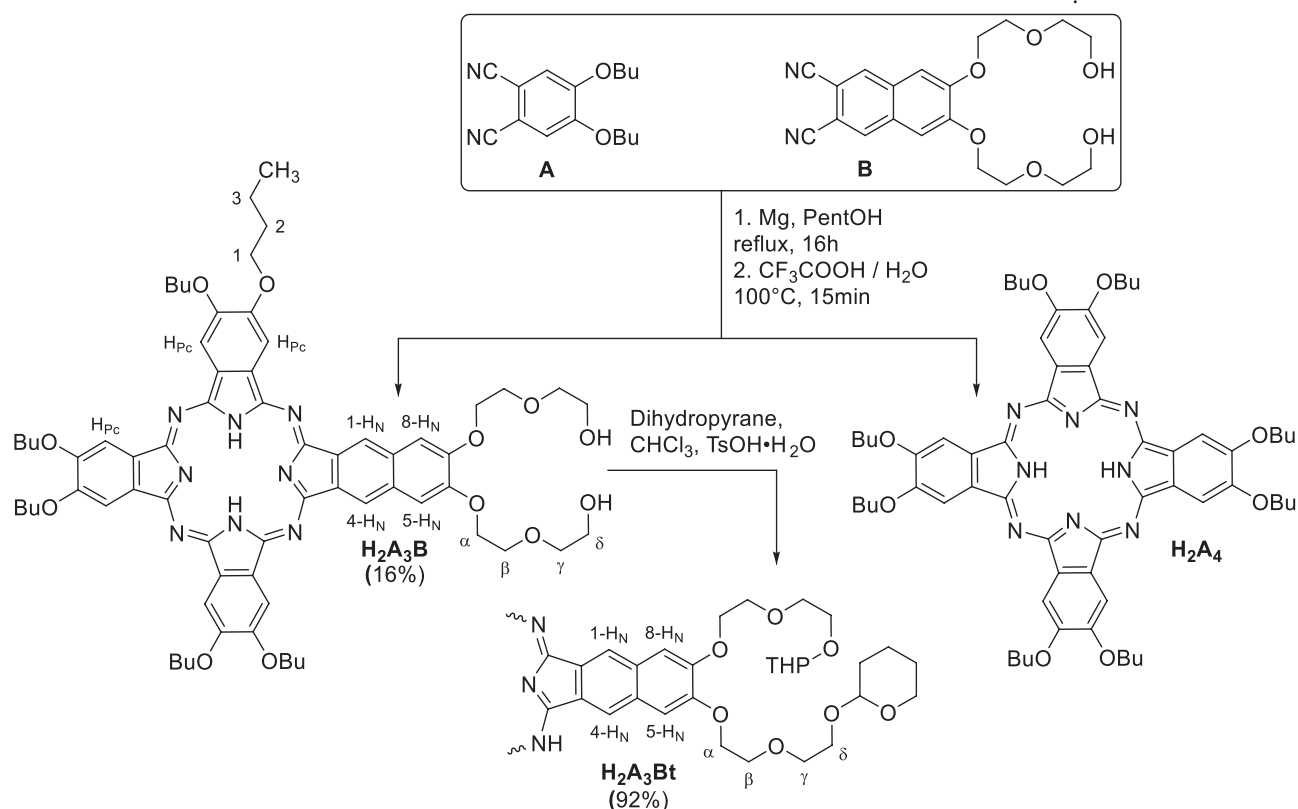
Results and Discussion

With the aim to synthesize low-symmetry benzo-annelated phthalocyanine **H₂A₃B** bearing anchor groups for their further immobilization on the surface of nanomaterials we used Mg-templated cross-condensation of phthalo- and naphthalonitriles **A** and **B** (Scheme 1). The use of magnesium as a template leads to increased yields compared to non-template reaction of cyclotetramerization.[15] The resulting mixture of magnesium complexes was demetalated with trifluoroacetic acid without isolation of individual compounds and the resulting mixture of ligands was separated by column chromatography on alumina followed by fine purification using size-exclusion chromatography.

Further modification of the synthesized phthalocyanine with tetrahydropyranyl protective groups was performed via reaction of **H₂A₃B** with dihydropyrane catalyzed with TsOH (Scheme 1). The resulting **H₂A₃Bt** will be used as a precursor to novel sandwich complexes based on benzoannelated phthalocyanines similarly to our previous results.[6]

Characterization of **H₂A₃B** and **H₂A₃Bt** was performed using MALDI TOF mass spectrometry, UV-Vis and NMR spectroscopy. While UV-Vis spectra of both phthalocyanines had similar character in diluted solutions, **H₂A₃B** had markedly different intensities and ratios of absorbances of Q-bands in concentrated solutions, which could be caused by aggregation of π-extended molecules (Figure 1). UV-Vis spectrum of **H₂A₃Bt** showed a noticeable but less pronounced dependence of its character as a function of concentration.

The analysis of concentration dependencies of UV-Vis spectra *vs.* concentration of dissolved phthalocyanines was performed using the approximation proposed by N. Mataga,[16] who suggested using the equation (1) to estimate the number of molecules, *n* in the forming aggregate:

$$\lg\left[C_0 \cdot \left(1 - \frac{\varepsilon_{eff}}{\varepsilon_m}\right)\right] = \lg(n \cdot K) + n \cdot \lg\left[C_0 \cdot \frac{\varepsilon_{eff}}{\varepsilon_m}\right] \quad (1)$$

Scheme 1. Synthesis of A$_3$B-type benzoannelated phthalocyanines together with labeling of protons used for assignment of NMR spectra.

Here K is the approximate value of stability constant of the aggregate, ε_{eff} is the observed extinction coefficient at certain wavelength, equal to optical density A divided by concentration C_0 of the dissolved phthalocyanine and optical path. The value of ε_m corresponds to extinction coefficient of the monomeric compound at this wavelength, which can be taken from the UV-Vis spectrum of the most diluted solu-

tion. Thus, plotting $\lg[C_0 \cdot (1 - \varepsilon_{eff}/\varepsilon_m)]$ *vs.* $\lg[C_0 \cdot \varepsilon_{eff}/\varepsilon_m]$ should give a straight line with the slope close to the aggregation number, and indeed such linear dependencies were observed for Q-bands of both **H$_2$A$_3$B** and **H$_2$A$_3$Bt**. Their slopes were equal to 1.54 and 1.76, suggesting that aggregation of both phthalocyanines leads mainly to dimeric species, however the approximate character of the equation (1) does not allow to use it to separate spectra of aggregated phthalocyanines into spectra of monomers and individual aggregates.

Further analysis was based on equation (2), which represents the exact dependency of optical density at a certain wavelength as a function of the concentration C_0, extinction
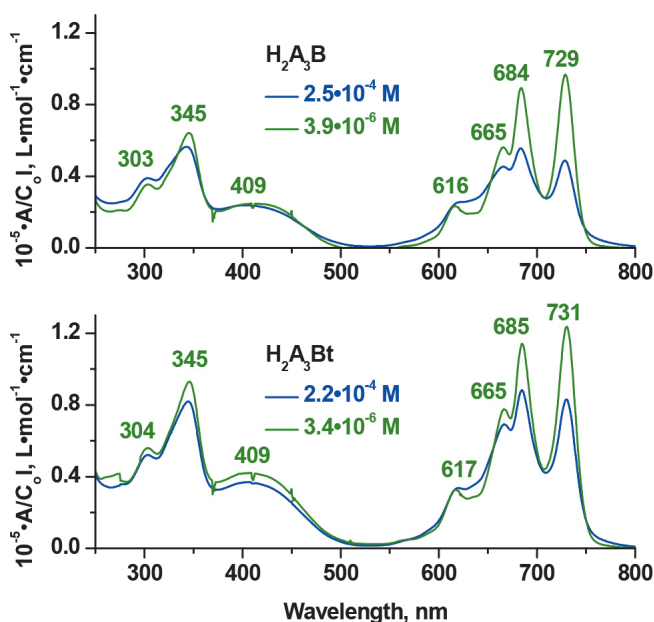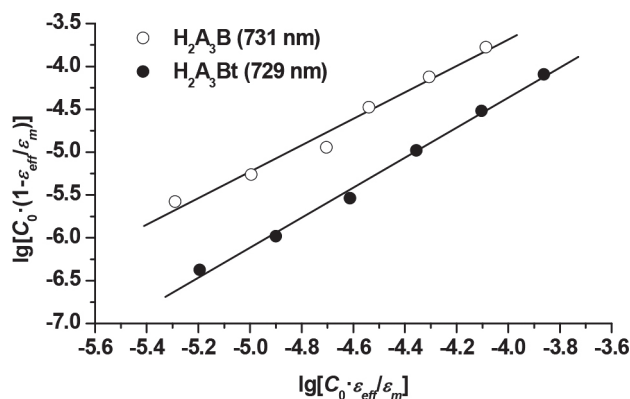

Figure 2. Graphical analysis of ε_{eff} values for determination of aggregation number n, obtained for long wavelength Q-bands of **H$_2$A$_3$B** (n = 1.54 ± 0.11, R2 = 0.980) and **H$_2$A$_3$Bt** (n = 1.75 ± 0.06, R2 = 0.995).

Figure 1. UV-Vis spectra of **H$_2$A$_3$B** and **H$_2$A$_3$Bt** in chloroform depending on concentration.

coefficients of monomeric and dimeric species ε_m and ε_d, as well as the equilibrium constant of dimerization process K_d.[17–19]

$$A = \left(\varepsilon_m - \frac{\varepsilon_d}{2} \right) \cdot \frac{\sqrt{1 + 8 \cdot C_0 \cdot K_d} - 1}{4K_d} + \frac{C_0 \cdot \varepsilon_d}{2} \qquad (2)$$

Thus, using nonlinear regression analysis we first determined ε_m for all bands in UV-Vis spectra of **H$_2$A$_3$B** and **H$_2$A$_3$Bt** and found the K_d values in the range of concentrations C_0 *ca.* 4–200 µM. The results of these calculations were in complete agreement with higher tendency of **H$_2$A$_3$B**, bearing free OH-groups to aggregation (lgK_d = 4.47) in comparison with its O-protected derivative **H$_2$A$_3$Bt** (lgK_d = 3.64).

Then, the array of concentration-dependent UV-Vis data for 31 wavelengths (from 600 to 750 nm with 5 nm step) was chosen, the values of ε_m and K_d from the previous step were fixed, and all other parameters were varied until convergence was achieved. The calculated UV-Vis spectra of monomers and dimers for both phthalocyanines are given in Figure 3.
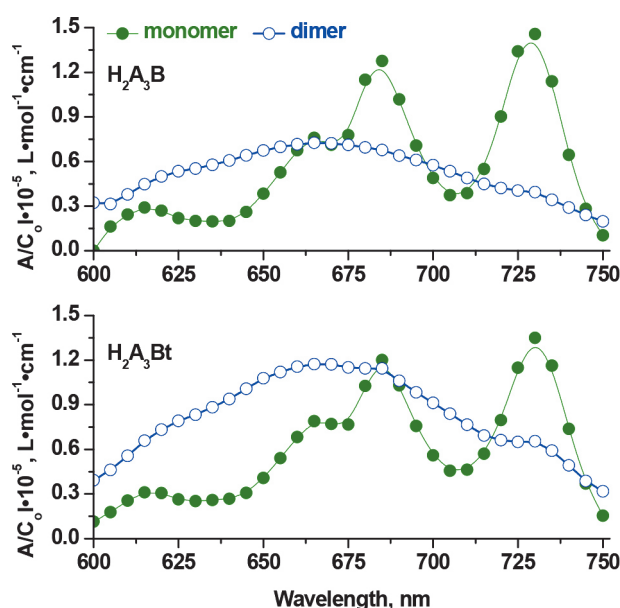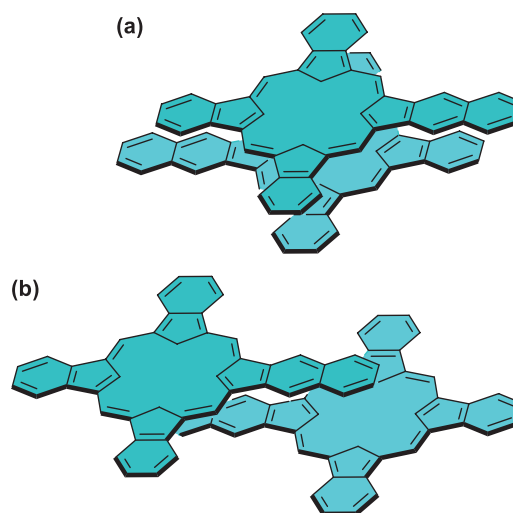

Figure 4. Possible architectures of head-to-tail H-dimers, formed by benzoannelated phthalocyanines in chloroform solution. Substituents are not shown for clarity.
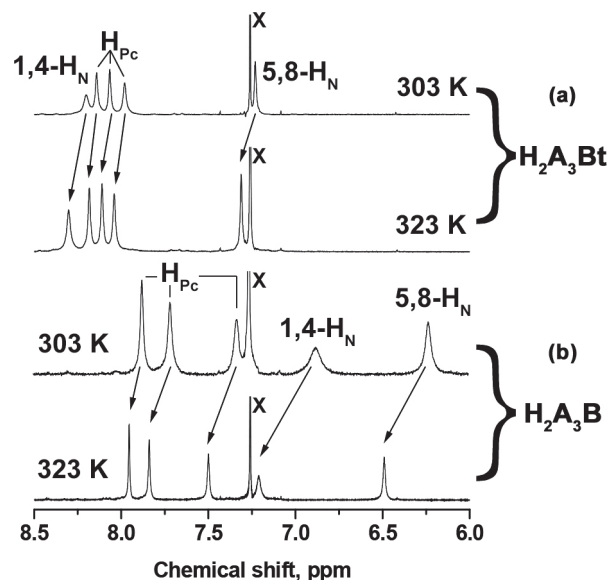

Figure 3. Calculated UV-Vis spectra of monomer and dimeric forms of **H$_2$A$_3$B** and **H$_2$A$_3$Bt** in chloroform.

Figure 5. Aromatic area of ^{1}H NMR spectra of **H$_2$A$_3$B** and **H$_2$A$_3$Bt** in CDCl$_3$ measured at 303 and 323 K. Labels of protons are given in Scheme 1.

The results of calculations showed that monomeric forms of both phthalocyanines reproduced the spectra of diluted solutions. They had typical appearance with split Q-bands and well-resolved vibronic satellites, while each of dimeric forms had only one broad structureless band with maximum at *ca.* 660 nm shifted hypsochormically with respect to Q-bands of monomeric compounds. Such spectral appearance is characteristic for the cofacial H-dimers, which however can have different degree of intermolecular overlap between neighboring aromatic systems (Figure 4).[20]

To get more insight into the structure of these dimers we used variable-temperature ^{1}H NMR spectroscopy. Measurements were performed for *ca.* 10 mM solutions of both

phthalocyanines at 303 and 323 K (Figure 5). At this concentration the fraction of monomers in solutions of **H$_2$A$_3$B** and **H$_2$A$_3$Bt** is below 10 %, thus the appearance of their NMR spectra is determined mainly by dimeric species.

In the case of **H$_2$A$_3$Bt** heating of the sample caused relatively small shifts of resonance signals of naphthalene protons (Figure 5a) and, generally the positions of these resonance signals were closer to their positions in the spectrum of the previously reported nonagregating phthalocyanine **H$_2$A′$_3$B** where six diisopropylphenoxy-groups were used as solubilizers instead of BuO-groups.[14] This observation indicates that the dimer formed by **H$_2$A$_3$Bt** can be similar to that shown in Figure 4a, with overlapping macrocyclic cores and naphthalene groups arranged outward.

To the contrast, ^{1}H NMR spectrum of the phthalocyanine **H$_2$A$_3$B** at 303 K was characterized by spectacular up-field shifts of both phthalic and naphthalenic resonance signals in comparison with the spectrum of **H$_2$A$_3$Bt** at the same temperature (Figure 5b). Upon the increase of the solution temperature from 303 to 323 K naphthalenic signals underwent a significant down-field shift, yet it did not afford complete disaggregation which is in line with higher stability of the dimeric form. The described behavior allows to propose the architecture of the dimer based on **H$_2$A$_3$B** as an assembly where naphthalene unit is located in vicinity to the tetrapyrrolic core of the neighboring molecule (Figure 4b), which results in up-field shift of 1,4-H$_N$ and 5,8-H$_N$ signals by *ca.* 1 ppm in comparison with **H$_2$A$_3$Bt**. The absence of such a strong shift in the case of O-protected derivative **H$_2$A$_3$Bt** evidences that terminal OH-groups in **H$_2$A$_3$B** contribute to stabilization of aggregated form, probably due to the formation of intermolecular hydrogen bonds. The difference in architectures of aggregates formed by **H$_2$A$_3$B** and **H$_2$A$_3$Bt** can be also responsible for the difference in extinction coefficients of dimers Q-bands which can be seen in Figure 2.

Conclusions

The influence of phthalocyanine aggregation on their photophysical properties is somewhat controversial. On one hand, it quenches excited states via nonradiative pathways, which can be a negative factor for fluorescent materials and photodynamic agents.[20] On the other hand, aggregation is known to enhance nonlinear optical properties of phthalocyanines improving their efficiency as optical limiters.[21–24] In the present work we showed how aggregation of benzoannelated phthalocyanines can be controlled by variation of functional groups at distant positions with respect to the tetrapyrrolic core. These results can contribute to elaboration of phthalocyanine-based materials with tuneable properties.[25]

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