Available online at www.sciencedirect.com

ScienceDirect

Mendeleev Commun., 2024, **34**, 167–169

Mendeleev Communications

pH-Dependent molecular switch based on P^{V} porphyrin

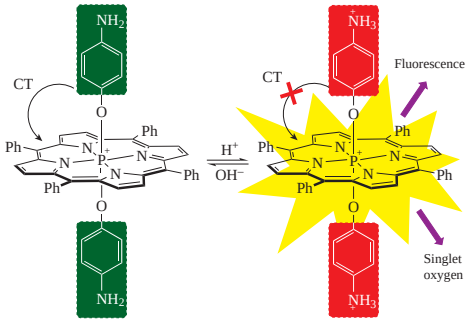
Inessa A. Efimova,[a] Evgeniya A. Safonova,*[a] Marina A. Polovkova,[a] Alexander G. Martynov,[a] Gayane A. Kirakosyan,[a,b] Aslan Yu. Tsivadze[a,b] and Yulia G. Gorbunova*[a,b]

[a] *A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, 119071 Moscow, Russian Federation. E-mail: safevgal@mail.ru, yulia@igic.ras.ru*

[b] *N. S. Kurnakov Institute of General and Inorganic Chemistry, Russian Academy of Sciences, 119991 Moscow, Russian Federation*

DOI: 10.1016/j.mencom.2024.02.003

Water-soluble phosphorus(V) porphyrin with *p*-aminophenoxy groups as axial ligands was obtained, and its photophysical and photochemical properties were investigated and rationalized using quantum chemical calculations. It was demonstrated that at pH ⩾ 6.1 this porphyrin did not emit or generate singlet oxygen, whereas at pH ⩽ 2.0 it completely converted into the N-protonated form, which exhibited fluorescence and the ability to generate singlet oxygen.



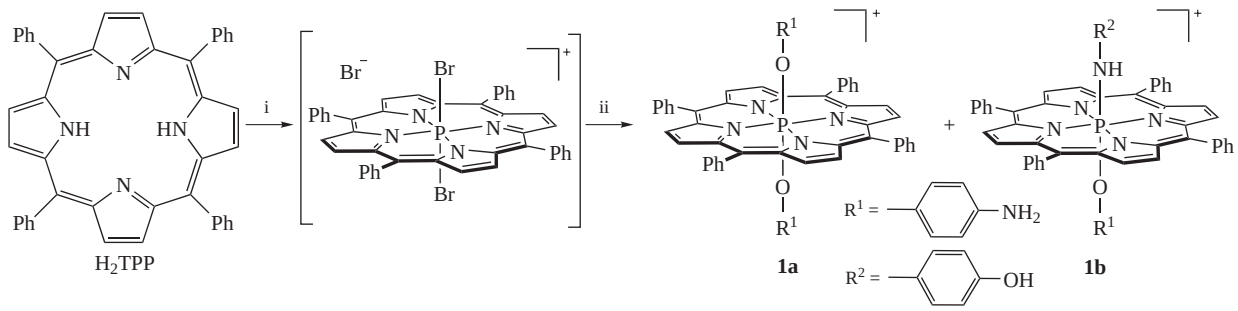
Keywords: molecular switches, porphyrin, phosphorus, fluorescence, singlet oxygen, protonation.

Interest in molecular switches is growing every year, since the principle of tuning the properties of a molecule by controlling an external parameter has prospects for application in various fields, both for the miniaturization of electronic devices[1–4] and for medical applications.[5–8] The 2016 Nobel Prize for the development of molecular machines[9–11] demonstrates the importance of research in this field.

Switching of physicochemical properties caused by different types of input signals has been demonstrated for systems based on tetrapyrrolic compounds.[12,13] Porphyrins, phthalocyanines and other tetrapyrrolic macrocycles are of particular interest in the field of molecular switches due to their intensive absorption in the visible spectral range and efficient optical response to various stimuli, such as light irradiation,[14,15] redox processes,[16–18] temperature changes[19,20] and the addition of ions or small molecules.[21–24] One of the significant types of molecular switches consists of pH-sensitive compounds that are capable of changing not only optical properties, but also photophysical and photochemical properties important for biological and photocatalytic applications.[25–30]

The introduction of P^{V} into porphyrin as a central atom is a powerful way to obtain efficient photosensitizers.[19,31–34] Additionally, the presence of axial ligands provides an opportunity to control the properties of the P^{V} porphyrin. Thus, complexes with aliphatic substituents in axial positions demonstrate high quantum yields of fluorescence and singlet oxygen generation.[19,31–33] For example, P^{V} porphyrin, containing one pyridyl and three phenyl groups in the *meso*-positions, exhibits quantum yields of 99 and 37% for singlet oxygen generation in $CHCl_3$ and DMSO, respectively.[32] The introduction of aromatic rings with donor groups (methyl, ethoxy and carbazolylvinylnaphthalimido) leads to the phenomenon of charge (or electron) transfer from the electron-donating system of the benzene ring to the positively charged central part of the porphyrin.[32,35–38] However, in the presence of an electron-withdrawing substituent (trifluoromethyl and cyano), the transfer process can be almost completely suppressed and the photosensitizing properties of the complex can be restored.[36,39] Consequently, a change in the electron density on the axial ligand by an external influence can lead to a switch in photophysical and photochemical properties. However, postsynthetic control of the photosensitizing properties of P^{V} porphyrins has not previously been described.

In this work, phosphorus(V) porphyrin **1a** containing a *p*-aminophenol fragment as axial groups was synthesized, and it was shown



Scheme 1 *Reagents and conditions*: i, $POBr_3$ (25 equiv.), pyridine, reflux, 30 min; ii, *p*-aminophenol (50 equiv.), 120 °C, 5 min.

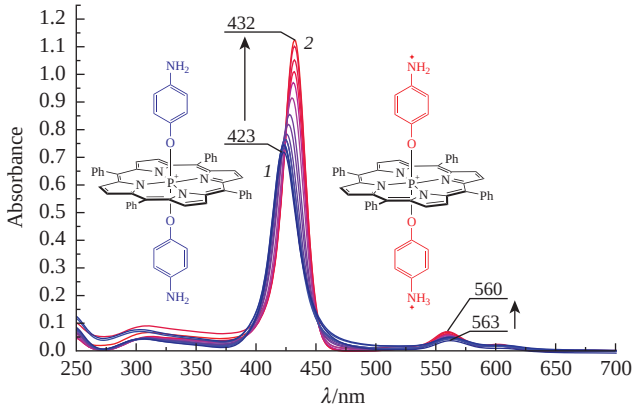


Figure 1 UV-VIS spectra of an aqueous solution of porphyrin **1a** when changing pH from (*1*) 6.1 to (*2*) 2.0.

that the photophysical and photochemical properties of the resulting complex can be switched by changing the pH of the medium.

The target compound **1a** was synthesized from H_2TPP and $POBr_3$ in pyridine (Scheme 1). In the first step, the intermediate dibromophosphorus(V) porphyrin $[(TPP)PBr_2]^+$ was formed, and in the second step, *p*-aminophenol was added to replace the axial Br ligands. It is important to mention that, in contrast to previously published methods for replacing axial Br ligands in P^V porphyrin at room temperature,[21,32,40–42] the addition of *p*-aminophenol was carried out in refluxing pyridine immediately after complete conversion of H_2TPP. During the reaction, two products are formed that differ in the mode of coordination of the *p*-aminophenol fragment: target complex **1a** containing the axial P–$OC_6H_4NH_2$ bond and by-product **1b** (see Scheme 1). The formation of two complexes **1a** and **1b** with different axial groups (ratio **1a**/**1b** = 2 : 1) was confirmed by NMR spectroscopy data (Figures S1 and S2, see Online Supplementary Materials). The isolated complex **1a** was characterized by UV-VIS (Figure 1), NMR (^{1}H, ^{13}C, ^{31}P, ^{1}H–^{15}N HMBC) (Figures 2 and S2–S4) and ESI HRMS (Figure S5). The formation of isomeric by-product **1b** was also confirmed by ^{1}H and ^{31}P NMR spectroscopy (Figures S2 and S6).

The mode of coordination of the *p*-aminophenol fragment in porphyrin **1a** was further confirmed by ^{1}H–^{15}N HMBC NMR spectroscopy (see Figure 2). In the ^{15}N NMR spectrum, a weaker signal at 185 ppm correlates with a doublet of pyrrole β-protons of the porphyrin ring. At the same time, the lower intensity signal of the amino group at 53 ppm correlates with a doublet at 5.29 ppm, corresponding to the *meta*-protons of the axial ligands, which indicates the coordination of *p*-aminophenol in product **1a** through the O atom.

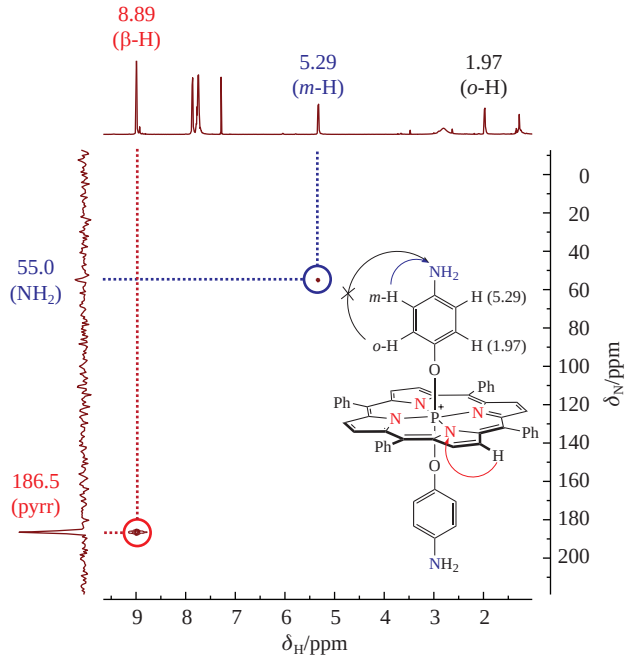


Figure 2 ^{1}H–^{15}N HMBC spectrum of complex **1a** ($CDCl_3$, 600 MHz).

The UV-VIS spectra of porphyrin **1a** show characteristic absorption in the Q-band region at 561 nm in DMSO solution (Figure S7) and at 563 nm in H_2O solution (see Figure 1). The Soret band is observed at 430 and 423 nm in DMSO and H_2O solutions, respectively. Upon addition of acid, a significant bathochromic shift of the Soret band up to 432 nm was observed, indicating the transition of porphyrin **1a** to the protonated form **1a**+2H$^+$. Spectrophotometric titration of an aqueous solution of porphyrin **1a** with 1 mM HCl demonstrated that complex **1a** exists in its initial form at pH ⩾ 6.1 (Figures 1 and S8). Upon acidification, a gradual shift of the Soret and Q bands was observed. The initial form **1a** and the protonated form **1a**+2H$^+$ are in equilibrium in the pH range from 2.0 to 6.1. Complete conversion of form **1a** to the protonated form occurs at pH ⩽ 2.0.

Complex **1a** in the initial state does not fluoresce at room temperature either in DMSO or in water, but fluorescence appears upon acidification (Figures 3, S9 and Table S1, see Online Supplementary Materials). This phenomenon can be explained by the fact that in complex **1a** there is a charge transfer from the axial ligand to the porphyrin ring, by analogy with data published previously.[30,33] Protonation of amino groups suppresses the charge transfer process and restores the fluorescent properties of the porphyrin. Similarly, complex **1a** is unable to generate singlet oxygen, in contrast to the protonated form **1a**+2H$^+$ (see Table S1). It should also be noted that complex **1a** is photostable, since when a solution of complex **1a** in DMSO is irradiated with a laser with a wavelength of 405 nm for 2 h, no decrease in the intensity of the absorption bands is observed.

A simplified TD-DFT approximation, sTD-DFT,[43,44] was used to calculate the orbital composition and vertical excitations in the UV-VIS spectra of the starting porphyrin **1a** and its N-protonated form **1a**+2H$^+$ (Table S2). Geometry optimization was performed using the composite electron-structure method r^{2}SCAN-3c[45] in aqueous media using a solvation model based on density (SMD).[46] sTD-DFT calculations were performed using the CAM-B3LYP range-separated functional and the 6-31G(d) basis set in aqueous media simulated by SMD. Then the frontier orbitals of the P^V porphyrins, the so-called Gouterman orbitals,[47] were inspected. This analysis showed that the localization of these orbitals depends on the protonation state of the axial aromatic groups (Figure 4). Thus, the pair of lowest unoccupied orbitals (LUMOs) of both complexes is localized on the porphyrin macrocycles, but in the case of the nonprotonated complex **1a**, the highest occupied orbitals (HOMOs) are delocalized on both the porphyrin ring and the axial ligands. As a result, the excitations

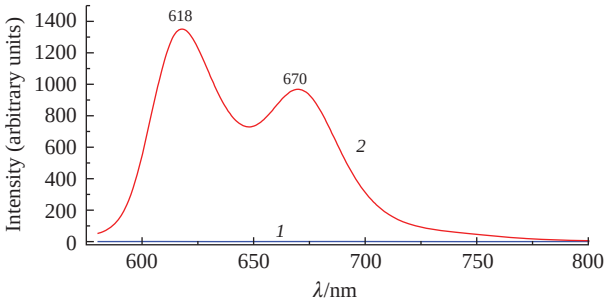


Figure 3 Fluorescence spectra of (*1*) the initial form **1a** and (*2*) the protonated form **1a**+2H$^+$ in aqueous solution.

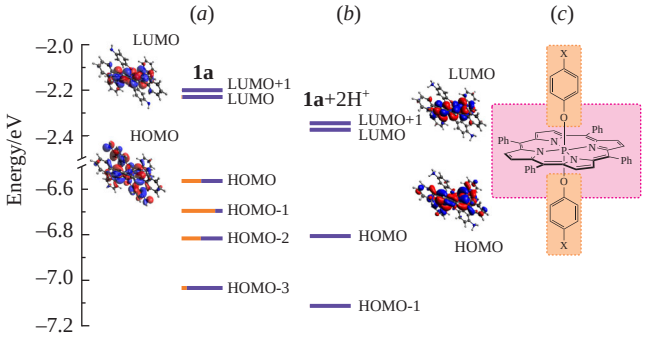


Figure 4 Frontier molecular orbital diagrams of (*a*) complex **1a** and (*b*) its protonated form **1a**+2H$^+$, showing the contributions of the porphyrin ring (violet part) and axial ligands (orange part) according to (*c*) the partitioning scheme.

of the Q and Soret bands in the starting complex have a significant charge-transfer character, which can be the cause of both fluorescence quenching and suppression of singlet oxygen generation.

However, once the amino groups of the axial ligands are protonated, both HOMO-1/HOMO and LUMO/LUMO+1 pairs are localized only on the porphyrin part, thus suppressing charge transfer. Deactivation of porphyrin-centered excited states gives rise to both fluorescence and the generation of singlet oxygen. A similar enhancement of fluorescence has been reported for porphyrazine derivatives conjugated to aza-crown moieties, since these receptor groups can bind alkali metal ions, blocking charge transfer from their nitrogen atoms to the porphyrazine macrocycle.[48] The observed bathochromic shift of the Soret band upon protonation is well reproduced by theoretical calculations (Table S2).

In summary, an approach has been developed for the synthesis and isolation of phosphorus(V) porphyrin with *p*-aminophenoxy groups as axial ligands. It has been found that when *p*-aminophenol reacts with dibromophosphorus(V) porphyrin, two isomers are formed. The mode of coordination of the *p*-aminophenol fragment was clarified using two-dimensional NMR spectroscopy. The photophysical and photochemical properties of porphyrin **1a** were studied at various pH values. It has been demonstrated that protonation of the compound leads to the appearance of both fluorescence and the ability to generate singlet oxygen due to the suppression of the charge transfer process.

This work was supported by the Russian Science Foundation (grant no. 22-23-01078). The measurements were performed using equipment of CKP FMI IPCE RAS and IGIC RAS.

Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2024.02.003.

References

1 J. L. Zhang, J. Q. Zhong, J. D. Lin, W. P. Hu, K. Wu, G. Q. Xu, A. T. S. Wee and W. Chen, *Chem. Soc. Rev.*, 2015, **44**, 2998.
2 H. Wang, H. K. Bisoyi, X. Zhang, F. Hassan and Q. Li, *Chem. – Eur. J.*, 2022, **28**, e202103906.
3 W. Liu, S. Yang, J. Li, G. Su and J.-C. Ren, *Wiley Interdiscip. Rev.: Comput. Mol. Sci.*, 2021, **11**, e1511.
4 R. Benny, D. Sahoo, A. George and S. De, *ChemistryOpen*, 2022, **11**, e202200128.
5 M. Natali and S. Giordani, *Chem. Soc. Rev.*, 2012, **41**, 4010.
6 D. Cardoso and E. Perucha, *Clin. Sci.*, 2021, **135**, 1389.
7 D. Fang and J. Zhu, *Cell. Mol. Life Sci.*, 2020, **77**, 289.
8 A. S. Popov, A. A. Efimova, A. V. Kazantsev, D. A. Erzunov, N. V. Lukashev, I. D. Grozdova, N. S. Melik-Nubarov and A. A. Yaroslavov, *Mendeleev Commun.*, 2021, **31**, 827.
9 B. L. Feringa, *Angew. Chem., Int. Ed.*, 2017, **56**, 11060.
10 J.-P. Sauvage, *Angew. Chem., Int. Ed.*, 2017, **56**, 11080.
11 J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2017, **56**, 11094.
12 A. G. Martynov, E. A. Safonova, A. Yu. Tsivadze and Y. G. Gorbunova, *Coord. Chem. Rev.*, 2019, **387**, 325.
13 R. C. H. Wong, P.-C. Lo and D. K. P. Ng, *Coord. Chem. Rev.*, 2019, **379**, 30.
14 V. Wellm, C. Näther and R. Herges, *J. Org. Chem.*, 2021, **86**, 9503.
15 V. Guerchais, L. Ordronneau and H. Le Bozec, *Coord. Chem. Rev.*, 2010, **254**, 2533.
16 A. G. Martynov, M. A. Polovkova, Y. G. Gorbunova and A. Yu. Tsivadze, *Molecules*, 2022, **27**, 6498.
17 L. Norel, C. Tourbillon, J. Warnan, J.-F. Audibert, Y. Pellegrin, F. Miomandre, F. Odobel and S. Rigaut, *Dalton Trans.*, 2018, **47**, 8364.
18 J. W. Canary, *Chem. Soc. Rev.*, 2009, **38**, 747.
19 I. E. Kolesnikov, A. A. Kalinichev, A. I. Solomatina, M. A. Kurochkin, I. N. Meshkov, E. Yu. Kolesnikov and Y. G. Gorbunova, *Sens. Actuators, A*, 2022, **347**, 113917.
20 Q. Fei, C. Wang, B. Wang, H. Xu, G. Li, Y. Huan, H. Shan and G. Feng, *Chem. Res. Chin. Univ.*, 2014, **30**, 379.
21 I. N. Meshkov, V. Bulach, Y. G. Gorbunova, N. Kyritsakas, M. S. Grigoriev, A. Yu. Tsivadze and M. W. Hosseini, *Inorg. Chem.*, 2016, **55**, 10774.
22 F. M. Kolomeychuk, E. A. Safonova, M. A. Polovkova, A. A. Sinelshchikova, A. G. Martynov, A. V. Shokurov, G. A. Kirakosyan, N. N. Efimov, A. Yu. Tsivadze and Y. G. Gorbunova, *J. Am. Chem. Soc.*, 2021, **143**, 14053.
23 A. G. Martynov, M. A. Polovkova, G. S. Berezhnoy, A. A. Sinelshchikova, V. N. Khrustalev, K. P. Birin, G. A. Kirakosyan, Y. G. Gorbunova and A. Yu. Tsivadze, *Inorg. Chem.*, 2021, **60**, 9110.
24 K. Norvaiša, M. Kielmann and M. O. Senge, *ChemBioChem*, 2020, **21**, 1793.
25 L. Li, A. V. Zhdanov and D. B. Papkovsky, *Sens. Actuators, B*, 2022, **371**, 132486.
26 N. Sh. Lebedeva, E. S. Yurina, Y. A. Gubarev, A. S. Semeikin and S. A. Syrbu, *Mendeleev Commun.*, 2022, **32**, 554.
27 D. Li, S. Cai, P. Wang, H. Cheng, B. Cheng, Y. Zhang and G. Liu, *Adv. Healthcare Mater.*, 2023, **12**, 2300263.
28 E. A. Safonova, F. M. Kolomeychuk, D. A. Gvozdev, A. Yu. Tsivadze and Y. G. Gorbunova, *Molecules*, 2023, **28**, 1094.
29 E. A. Safonova, I. N. Meshkov, M. A. Polovkova, M. V. Volostnykh, A. Yu. Tsivadze and Y. G. Gorbunova, *Mendeleev Commun.*, 2018, **28**, 275.
30 B.-D. Zheng, Z.-L. Huang, L.-L. Lv, W.-L. Lan, J.-Q. Hu, X. Li, B.-Y. Zheng, M.-R. Ke and J.-D. Huang, *J. Mater. Chem. B*, 2021, **9**, 2845.
31 T. Furuyama, T. Okujima, K. Muramatsu, Y. Takahashi, A. Mikami, T. Fukumura, S. Mori, T. Nakae, M. Takase, H. Uno and N. Kobayashi, *Eur. J. Org. Chem.*, 2019, 3224.
32 I. N. Meshkov, V. Bulach, Y. G. Gorbunova, F. E. Gostev, V. A. Nadtochenko, A. Yu. Tsivadze and M. W. Hosseini, *Chem. Commun.*, 2017, **53**, 9918.
33 I. E. Kolesnikov, M. A. Kurochkin, I. N. Meshkov, R. A. Akasov, A. A. Kalinichev, E. Yu. Kolesnikov, Y. G. Gorbunova and E. Lähderanta, *Mater. Des.*, 2021, **203**, 109613.
34 O. V. Batishchev, M. A. Kalutskii, E. A. Varlamova, A. N. Konstantinova, K. I. Makrinsky, Y. A. Ermakov, I. N. Meshkov, V. S. Sokolov and Y. G. Gorbunova, *Front. Mol. Biosci.*, 2023, **10**, 1192794.
35 K. Hirakawa and H. Segawa, *J. Photochem. Photobiol., A*, 1999, **123**, 67.
36 M. Fujitsuka, D. W. Cho, S. Tojo, A. Inoue, T. Shiragami, M. Yasuda and T. Majima, *J. Phys. Chem. A*, 2007, **111**, 10574.
37 K. Hirakawa and H. Segawa, *J. Photochem. Photobiol., A*, 2010, **213**, 73.
38 Y. Zhan, K. Cao, C. Wang, J. Jia, P. Xue, X. Liu, X. Duan and R. Lu, *Org. Biomol. Chem.*, 2012, **10**, 8701.
39 K. Hirakawa, K. Azumi, Y. Nishimura, T. Arai, Y. Nosaka and S. Okazaki, *J. Porphyrins Phthalocyanines*, 2013, **17**, 56.
40 K. Akiba, R. Nadano, W. Satoh, Y. Yamamoto, S. Nagase, Z. Ou, X. Tan and K. M. Kadish, *Inorg. Chem.*, 2001, **40**, 5553.
41 T. Barbour, W. J. Belcher, P. J. Brothers, C. E. F. Rickard and D. C. Ware, *Inorg. Chem.*, 1992, **31**, 746.
42 T. Furuyama, Y. Takahashi, T. Fukumura, A. C. C. Bacilla and N. Kobayashi, *J. Porphyrins Phthalocyanines*, 2020, **24**, 105.
43 C. Bannwarth and S. Grimme, *Comput. Theor. Chem.*, 2014, **1040**–**1041**, 45.
44 A. G. Martynov, J. Mack, A. K. May, T. Nyokong, Y. G. Gorbunova and A. Y. Tsivadze, *ACS Omega*, 2019, **4**, 7265.
45 S. Grimme, A. Hansen, S. Ehlert and J.-M. Mewes, *J. Chem. Phys.*, 2021, **154**, 064103.
46 A. V. Marenich, C. J. Cramer and D. G. Truhlar, *J. Phys. Chem. B*, 2009, **113**, 6378.
47 M. Gouterman, G. H. Wagnière and L. C. Snyder, *J. Mol. Spectrosc.*, 1963, **11**, 108.
48 L. Lochman, J. Svec, J. Roh, K. Kirakci, K. Lang, P. Zimcik and V. Novakova, *Chem. – Eur. J.*, 2016, **22**, 2417.

Received: 8th November 2023; Com. 23/7299