

Chemoselective detection of Ag⁺ in purely aqueous solution using fluorescence ‘turn-on’ probe based on crown-containing 4-methoxy-1,8-naphthalimide

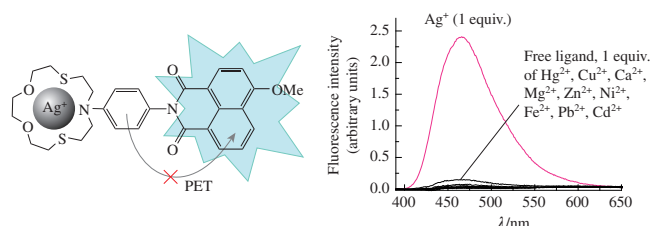
Pavel A. Panchenko,^{a,b} Anna S. Polyakova,^b Yurii V. Fedorov^a and Olga A. Fedorova^{a,b}

^a A. N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, 119991 Moscow, Russian Federation. Fax: +7 499 135 5085; e-mail: pavel@ineos.ac.ru

^b D. I. Mendeleev University of Chemical Technology of Russia, 125047 Moscow, Russian Federation

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A novel derivative of 4-methoxy-1,8-naphthalimide bearing *N*-phenylazadithia-15-crown-5 ether receptor has been demonstrated as the selective and sensitive fluorescent probe for the detection of silver(I) ions in purely aqueous solution at neutral pH.



Determination of transition and heavy metals in aqueous media, which exert hazardous effects on the environment, is of significant importance. Silver(I) is one among metals frequently used in various fields such as imaging, electronics, pharmacy, photography as well jewellery, table cutlery, and filters for water purifiers.¹ However, superabundance of silver can cause a strong poisoning to organisms.² Once it was absorbed in the human body, silver ions can displace essential metal ions such as Ca²⁺ and Zn²⁺ in hydroxyl apatite in bones. Moreover, the bioaccumulation and toxicity of silver ions through binding with various metabolites such as amine, carboxyl groups, and inactivating sulfhydryl enzymes have also been reported.³ The high concentration of Ag⁺ ion can lead to a variety of adverse health effects, brain damage, nerve damage, and disorders in immune system.

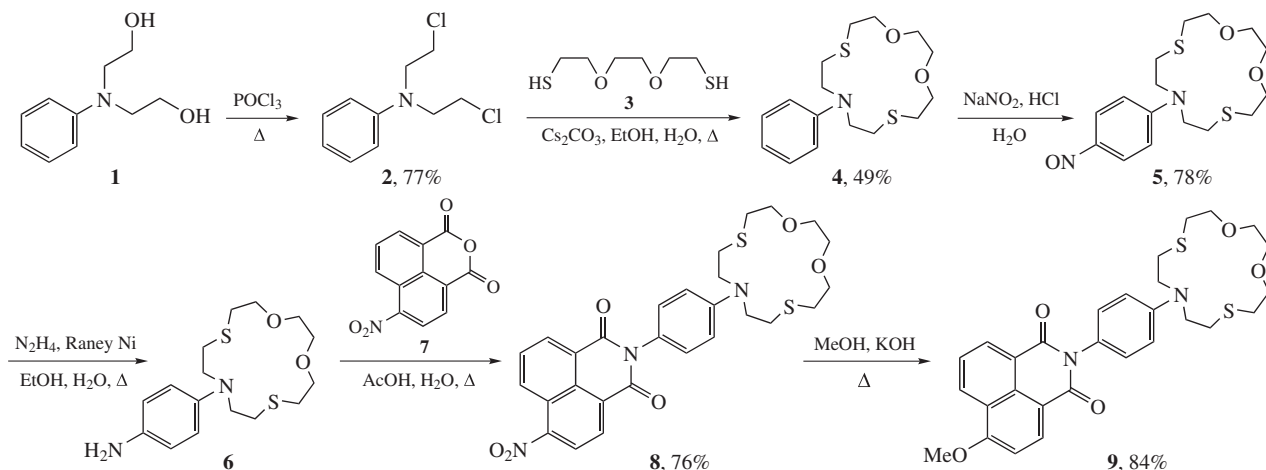
Some of the traditional methods such as spectrophotometry, atomic absorption spectrometry, stripping voltammetry, potentiometry, and inductively coupled plasma atomic emission spectrometry have been employed for the detection of silver ions. However, these methods are labor-intensive and expensive. In contrast, a fluorescence-based sensing provides significant advantages of simplicity, high sensitivity and selectivity, easy operation, and instant responses.⁴ The majority of sensors developed for heavy metal ions are based on the conventional fluorescence emission technique *via* quenching (‘on-off’ or ‘turn off’ switching) of the fluorescence intensity.⁵ In particular, a decrease in the emission signal upon coordination with Ag⁺ was observed quite often.⁶ Although the fluorescence quenching can be used for analytical measurements, ‘off-on’ intensity change is a more preferable case. In addition, the fluorescent chemosensors reported for the detection of Ag⁺ ions were mostly designed for organic solvents or mixed aqueous solutions.^{6(b),7}

In our previous work,⁸ we prepared fluorescent sensors containing benzo-15-crown-5 and *N*-phenylaza-15-crown-5 ether receptors as *N*-aryl substituents attached to *N*-imide atom of the well-known naphthalimide fluorophore. A distinct feature of those designed molecules is that the donor atoms (N or O) of receptor are conjugated with the π -system of *N*-phenyl moiety.

This led to an increased electron-releasing character of the receptor (as compared to crown ethers without an aromatic substituent) and, consequently, to a high optical response due to switching of photoinduced electron transfer (PET) from *N*-aryl moiety to naphthalimide chromophore upon binding to metal ions. The fluorescence enhancement by more than two orders of magnitude was observed, which was eventually anticipated, but not very often revealed for the majority of fluorescent PET sensors. Regardless of the achieved results, the prepared compounds could hardly be good candidates for the sensing of metal ions in aqueous environment since the water molecules may efficiently compete with the crown ethers, wherein only the oxygen and aniline nitrogen atoms are involved in the complex formation. The aim of the present work was to extend a pronounced PET switching effect in the emission spectra discovered for previously studied naphthalimides to selective sensing of Ag⁺ in water.

For this purpose, a novel derivative of 4-methoxy-1,8-naphthalimide bearing *N*-phenylazadithia-15-crown-5 ether receptor (compound **9**), which incorporates two sulfur atoms (known as the soft donors suitable for binding of cations with diffuse electron shell) in the structure of aza-15-crown-5 macrocycle, was prepared (Scheme 1).[†] In its structure, the 4-methoxynaphthalimide chromophore has been chosen as a fluorescent unit due to its high emission quantum yield in protic solvents such as water and alcohols. For instance, the emission quantum yield (ϕ^{fl}) of 4-methoxy-*N*-ethyl-1,8-naphthalimide is 0.64 in water and 0.71 in MeCN.¹⁰ This makes 4-methoxy-1,8-naphthalimide moiety quite attractive for the sensory applications as compared to commonly used 4-amino-naphthalimides, which usually demonstrate lower fluorescence efficiencies in polar protic environment, *e.g.*, the ϕ^{fl} values of 4-amino-*N*-phenyl-1,8-naphthalimide in MeCN and water are

[†] Compounds **2**,^{9(b)} **4**,^{9(c),(d)} **5**^{9(c)} and **6**^{9(e)} were previously reported, however, methods used for the preparation of **4** and **6** were different from those reported herein. See Online Supplementary Materials for synthetic procedures.



Scheme 1

0.52 and 0.091, respectively.¹¹ Moreover, the contribution of non-fluorescent twisted intramolecular charge transfer states in the case of 4-(*N,N*-dialkylamino)naphthalimides and similar compounds could also affect the spectral characteristics.¹²

The signaling behavior of sensor **9** was investigated towards various metal ions (Ag^+ , Hg^{2+} , Cu^{2+} , Ca^{2+} , Pb^{2+} , Cd^{2+} , Ni^{2+} , Zn^{2+} , Mg^{2+} , and Fe^{2+}). First, its spectral characteristics were studied. Similarly to other 4-methoxy-1,8-naphthalimides,¹³ compound **9** exhibited the broad-band charge transfer absorption and fluorescence in aqueous solution with maxima positions at 374 and 458 nm, respectively (Figure S1, Online Supplementary Materials). However, the emission quantum yield was found to be very low ($\phi^{\text{fl}} = 0.0002$). According to our previous results,^{8(c),(d),(f)} such behavior can be explained by the occurrence of PET between the *N*-aryl group and naphthalimide moiety in the excited state. Classical fluorophore–space–receptor architecture of molecule **9** was also confirmed by the optimized ground state geometry (Figure S2) showing nearly orthogonal orientation of the naphthalimide and phenyl ring planes and thus the lack of conjugation between the receptor and chromophore.

Next, the influence of pH on the fluorescence of compound **9** was examined (Figure S3). An obvious increase of intensity in the emission spectrum was observed with decreasing pH below 4.0, which could be attributed to the inhibition of PET process. No change in the fluorescence intensity occurred at pH higher than 6.0, which makes compound **9** attractive for its application by both physiological and environmental criteria. Based on these results, we have selected pH 7.3 media buffered with 10 mM HEPES for the measurements of sensing properties.

Figure 1(a) shows that the emission at 460 nm was dramatically enhanced with raising concentration of Ag^+ added to the 5 μM solution of compound **9**, while the changes in the absorption spectrum were negligible (Figure S4). The fluorescence enhancement was assigned to the formation of complex with the Ag^+ to ligand **9** ratio of 1 : 1 and applied for the calculation of its stability constant (K_{assoc}). The evidence of formation of **9**· Ag^+ complex was approved by the Job's plot, which shows the maximum fluorescence intensity of the mixed solution containing ligand **9** and silver(I) perchlorate at *ca.* 0.5 molar fraction of Ag^+ [Figure 1(b)].

The ESI MS analysis of the acetonitrile solution of compound **9** in the presence of 1 equiv. of AgClO_4 revealed the major signal at *m/z* 661.13 (calc., *m/z*: 661.09) corresponding to cation [**9**+ Ag]⁺ (Figure S5). Based on the titration data, the value of $\log K_{\text{assoc}}$ was estimated as 6.39 ± 0.07 . Moreover, the increase in fluorescence intensity of **9** with increasing amount of Ag^+ added (0.5–3.5 μM) demonstrated a good linearity with the correlation

coefficient of 0.99 (Figure S6). From the slope of that calibration plot (*r*) and standard deviation of the blank solution (S_Y), the detection limit for Hg^{2+} (C_{DL}) was found to be 0.38 μM according to equation (1):¹⁴

$$C_{\text{DL}} = 3S_Y/r. \quad (1)$$

Note that the obtained value of C_{DL} is quite close to the secondary maximum contaminant level of silver(I) in drinking water (0.1 mg dm^{-3} or 0.93 μM) established by the US Environmental Protection Agency.¹⁵

To evaluate the selectivity of probe of **9** in aqueous solution, the fluorescence responses to various metal ions were investigated. Figure 2(a) shows that the addition of Ag^+ (1 equiv.) induced significant spectral changes, while no distinct fluorescence enhancements[‡] were observed in the presence of other metal ions

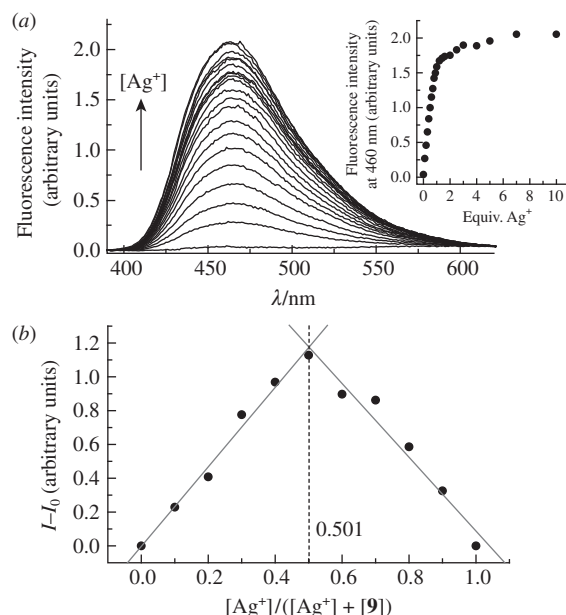


Figure 1 (a) Fluorescence emission spectra of compound **9** (5 μM) upon addition of Ag^+ (0–50 μM) and (b) Job's plot showing the difference between fluorescence intensity before (I_0) and after (I) addition of Ag^+ vs. molar fraction of Ag^+ at the constant $[\text{Ag}^+] + [\mathbf{9}]$ value (5 μM) in water at pH 7.3 (10 mM HEPES buffer). Excitation wavelength was 375 nm. The inset shows the fluorescence intensity at 460 nm as a function of added equivalents of Ag^+ .

[‡] The value of fluorescence enhancement was calculated as the ratio between the emission intensity at 460 nm measured after the addition of metal ion and that measured before the addition.

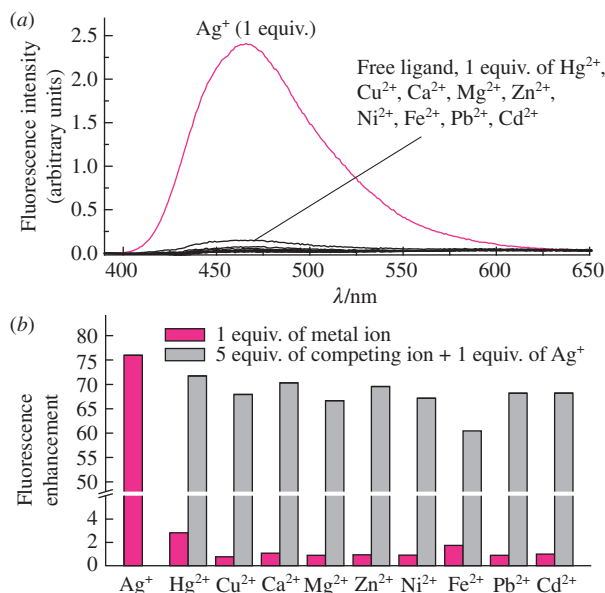


Figure 2 (a) Fluorescence spectra of compound **9** (5 μM) upon addition of Ag⁺, Hg²⁺, Fe²⁺, Cu²⁺, Zn²⁺, Pb²⁺, Cd²⁺, Ni²⁺, Ca²⁺, and Mg²⁺ (1 equiv.) in water at pH 7.3 (10 mM HEPES buffer); (b) selectivity of **9** for Ag⁺. Excitation wavelength was 375 nm.

(1 equiv.). The competition experiments were also conducted [Figure 2(b)]. In a typical procedure, the emission spectrum was measured before and after the addition of other ions (5 equiv.) to the solution of **9** (5 μM) containing Ag⁺ (1 equiv.). As one can see, the presence of Cu²⁺, Ca²⁺, Pb²⁺, Mg²⁺, Zn²⁺, Ni²⁺, or Cd²⁺ did not cause any pronounced signal interference, while there was a small effect in the cases of Hg²⁺ and Fe²⁺. Noteworthy, such a low response of sensor **9** to mercury(II) cations was first seemed quite surprising, since azadithia-15-crown-5 ether is the known ionophore for Hg²⁺.¹⁶ The analysis of conditions under which this receptor was capable to bind Hg²⁺ effectively has shown that mostly pure organic solvents (acetonitrile,^{16(a),(b)} chloroform,^{16(c)} or THF^{16(d)}) were used as the media. However, the similar high selectivity to Ag⁺ over Hg²⁺ was observed in aqueous 50 vol% ethanol at pH 7.2.^{6(b)} This is consistent with the fact¹⁷ that mercury(II) ion is completely hydrolyzed at neutral pH and exists in the form of Hg(OH)₂, while Ag⁺ is much less subjected to the hydrolysis. In our recent work,^{16(e)} we also reported that the fluorescence response of sensor molecule bearing the same azadithia-15-crown-5 receptor and 4-amino-1,8-naphthalimide chromophore to Hg²⁺ in acidic methanol–water solution (pH 4.7) or in acetonitrile was fairly high.

In summary, the novel crown-containing 4-methoxy-1,8-naphthalimide derivative **9** has been synthesized and evaluated with respect to its ability to serve as the fluorescent PET chemosensor for silver(I) ion. The fluorescence intensity of compound **9** is enhanced in the presence of Ag⁺ due to the formation of highly emissive complex **9**·Ag⁺, where the PET process is hampered. A good selectivity of the new sensor for the quantification of silver(I) content in purely aqueous solutions at the micromolar level has been demonstrated.

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Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2019.03.012.

References

- (a) C. Chen, H. Liu, B. Zhang, Y. Wang, K. Cai, Y. Tan, C. Gao, H. Liu, C. Tan and Y. Jiang, *Tetrahedron*, 2016, **72**, 3980; (b) S. Y. Lee, K. H. Bok and C. Kim, *RSC Adv.*, 2017, **7**, 290.
- (a) K. Velmurugan, A. Thamilselvan, R. Antony, V. R. Kannan, L. Tang and R. Nandhakumar, *J. Photochem. Photobiol., A*, 2017, **333**, 130; (b) A. Affrose, S. D. S. Parveen, B. S. Kumar and K. Pitchumani, *Sens. Actuators, B*, 2015, **206**, 170.
- Q. L. Feng, J. Wu, G. Q. Chen, T. N. Kim and J. O. Kim, *J. Biomed. Mater. Res.*, 2000, **52**, 662.
- (a) M. Formica, V. Fusi, L. Giorgi and M. Micheloni, *Coord. Chem. Rev.*, 2012, **256**, 170; (b) M. H. Lee, J. S. Kim and J. L. Sessler, *Chem. Soc. Rev.*, 2015, **44**, 4185; (c) S. A. Gorbato, M. A. Kozlov, I. E. Zlobin, A. V. Kartashov, I. V. Zavarzin and Yu. A. Volkova, *Mendeleev Commun.*, 2018, **28**, 615.
- P. A. Panchenko, O. A. Fedorova and Yu. V. Fedorov, *Russ. Chem. Rev.*, 2014, **83**, 155.
- (a) A. D. Arulraj, R. Devasenathipathy, S.-M. Chen, V. S. Vasantha and S.-F. Wang, *Sens. Biosens. Res.*, 2015, **6**, 19; (b) T. Chen, W. Zhu, Y. Xu, S. Zhang, X. Zhang and X. Qian, *Dalton Trans.*, 2010, **39**, 1316.
- C. S. Park, J. Y. Lee, E.-J. Kang, J.-E. Lee and S. S. Lee, *Tetrahedron Lett.*, 2009, **50**, 671.
- (a) P. A. Panchenko, Y. V. Fedorov, V. P. Perevalov, G. Jonusauskas and O. A. Fedorova, *J. Phys. Chem. A*, 2010, **114**, 4118; (b) P. A. Panchenko, Y. V. Fedorov, O. A. Fedorova, B. A. Izmailov, V. A. Vasnev, V. V. Istratov, E. A. Makeeva, M. N. Rumyantseva and A. M. Gaskov, *Mendeleev Commun.*, 2011, **21**, 12; (c) A. N. Sergeeva, P. A. Panchenko, Yu. V. Fedorov and O. A. Fedorova, *Prot. Met. Phys. Chem. Surf.*, 2012, **48**, 524 (*Fizikokhimiya Poverkhnosti i Zashchita Materialov*, 2012, **48**, 440); (d) P. A. Panchenko, Y. V. Fedorov, O. A. Fedorova and G. Jonusauskas, *Dyes Pigm.*, 2013, **98**, 347; (e) P. A. Panchenko, V. V. Park, O. A. Fedorova, Yu. V. Fedorov and E. A. Kataev, *Russ. Chem. Bull., Int. Ed.*, 2015, **64**, 1871 (*Izv. Akad. Nauk, Ser. Khim.*, 2015, 1871); (f) P. A. Panchenko, Y. V. Fedorov, O. A. Fedorova and G. Jonusauskas, *Phys. Chem. Chem. Phys.*, 2015, **17**, 22749.
- (a) S. L. Selektor, L. B. Bogdanova, A. V. Shokurov, P. A. Panchenko, O. A. Fedorova and V. V. Arslanov, *Makroeterotsikly/Macroheterocycles*, 2014, **7**, 311; (b) R. C. Elderfield, I. S. Covey, J. B. Geiduschek, W. L. Meyer, A. B. Ross and J. H. Ross, *J. Org. Chem.*, 1958, **23**, 1749; (c) A. B. Descalzo, R. Martínez-Máñez, R. Radeaglia, K. Rurack and J. Soto, *J. Am. Chem. Soc.*, 2003, **125**, 3418; (d) D. Jiménez, R. Martínez-Máñez, F. Sancenón, J. V. Ros-Lis, J. Soto, Á. Benito and E. García-Breijo, *Eur. J. Inorg. Chem.*, 2005, 2393; (e) M. Tian and H. Ihmels, *Eur. J. Org. Chem.*, 2011, 4145.
- A. Pardo, J. M. L. Poyato, E. Martín, J. J. Camacho, D. Reyman, M. F. Braña and J. M. Castellano, *J. Photochem. Photobiol., A*, 1989, **46**, 323.
- P. A. Panchenko, Yu. V. Fedorov, O. A. Fedorova, V. P. Perevalov and G. Jonusauskas, *Russ. Chem. Bull., Int. Ed.*, 2009, **58**, 1233 (*Izv. Akad. Nauk, Ser. Khim.*, 2009, 1199).
- (a) Z. Szakács, S. Rousseva, M. Bojtár, D. Hessz, I. Bitter, M. Kállay, M. Hilbers, H. Zhang and M. Kubinyi, *Phys. Chem. Chem. Phys.*, 2018, **20**, 10155; (b) P. A. Panchenko, A. N. Arkhipova, O. A. Fedorova, Y. V. Fedorov, M. A. Zakharko, D. E. Arkhipov and G. Jonusauskas, *Phys. Chem. Chem. Phys.*, 2017, **19**, 1244; (c) A. N. Arkhipova, P. A. Panchenko, Yu. V. Fedorov and O. A. Fedorova, *Mendeleev Commun.*, 2017, **27**, 53.
- (a) E. Martin, R. Weigand and A. Pardo, *J. Lumin.*, 1996, **68**, 157; (b) G. J.-F. Demets, E. R. Triboni, E. B. Alvarez, G. M. Arantes, P. B. Filho and M. J. Politi, *Spectrochim. Acta, Part A*, 2006, **63**, 220.
- H.-P. Looock and P. D. Wentzell, *Sens. Actuators, B*, 2012, **173**, 157.
- K. S. Park, J. Y. Lee and H. G. Park, *Chem. Commun.*, 2012, **48**, 4549.
- (a) T. Ábalos, D. Jiménez, R. Martínez-Máñez, J. V. Ros-Lis, S. Royo, F. Sancenón, J. Soto, A. M. Costero, S. Gil and M. Parra, *Tetrahedron Lett.*, 2009, **50**, 3885; (b) E. Chernikova, D. Berdnikova, Y. Fedorov, O. Fedorova, A. Peregodov and L. Isaacs, *Chem. Commun.*, 2012, **48**, 7256; (c) C. H. Jeon, J. Lee, S. J. Ahn and T. H. Ha, *Tetrahedron Lett.*, 2013, **54**, 6841; (d) S. Atılgan, I. Kutuk and T. Özdemir, *Tetrahedron Lett.*, 2010, **51**, 892; (e) P. A. Panchenko, Y. V. Fedorov and O. A. Fedorova, *J. Photochem. Photobiol., A*, 2018, **364**, 124.
- A. Walcarus, M. Etienne and C. Delacote, *Anal. Chim. Acta*, 2004, **508**, 87.

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