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Short Communication

Reusable colorimetric and fluorescent chemosensors based on 1,8-naphthalimide derivatives for fluoride ion detection

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ABSTRACT

Two 1, 8-naphthalimide derivatives, 2-(2-ethylhexyl)-6-(2-(4-(5-phenyl-1,3,4-oxadiazol-2-yl)benzylidene)hydrazinyl)-1H-benzo[*de*]isoquinoline-1,3(2H)-dione (named as NAOZ) and 2-(2-ethylhexyl)-6-(2-(4-(5-phenyl-1,3,4-thiadiazol-2-yl)benzylidene)hydrazinyl)-1H-benzo[*de*]isoquinoline-1,3(2H)-dione (named as NATZ), containing hydrazone and thiadiazole/oxadiazole, were successfully synthesized. Compounds NAOZ and NATZ were further served as efficient reversible colorimetric and fluorescent chemosensors for fluoride ion over a wide range of other anions (Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts) because fluoride ion can deprotonate the hydrazone moiety, leading to the observed long-wavelength color change. Interestingly, CO_2 can recover the charge transfer (CT) absorption and photoluminescence intensities of compound NAOZ/NATZ + F^-, because CO_2 can react with a small amount of water to form acids, which can provide protons.

1. Introduction

The development of chemical sensors for the recognition and sensing of anions has become important in supramolecular chemistry because anions play vital roles in a wide range of biological and environmental processes [1–14]. Among all anions, the recognition and detection of fluoride ion has become a fast growing field of research because they are important in human physiology and environment [15–19]. Therefore, measuring the exact concentration of fluoride ions is important. A popular design approach for chemical sensors used to recognize and sense fluoride ion involves the synthesis of chromophores/fluorophores furnished with one or more charged (such as thioureas and imidazoles with NH group) or charged-neutral (such as silyl ether materials) recognition moieties [20–26]. However, the development of fluoride ion sensors with a large hypsochromic shift or bathochromic shift has been challenging. Large hypsochromic or bathochromic shifts are crucial to the development of excellent fluoride ion sensors, which are utilized as naked eye colorimetric sensors. Numerous excellent colorimetric and fluorescent chemosensors for fluoride ion have been synthesized [27–31], but the development of reusable colorimetric and fluorescent chemosensors for fluoride ion has been rarely explored.

1,8-Naphthalimide derivatives have been widely investigated because of their interesting and excellent electro-optical properties [32–36]. In general, the backbone of 1,8-naphthalimide can be easily functionalized along two directions, namely, 1,8 and 4,5 positions. Thus, 1,8-naphthalimide derivatives have been applied to recognize and sense fluoride ion [37–43]. As a 1,8-naphthalimide derivative, 1,8-naphthalimide hydrazones are conjugated organic compounds with a planar structure because of their amino conjugation effect [44,45]. We are interested in the synthesis of 1,8-naphthalimide furnished with one hydrazine and thiadiazole/oxadiazole to develop naked eye colorimetric sensors for the recognition and sensing of fluoride ions.

Herein, two 1,8-naphthalimide derivatives, 2-(2-ethylhexyl)-6-(2-(4-(5-phenyl-1,3,4-oxadiazol-2-yl)benzylidene)hydrazinyl)-1H-benzo[*de*]isoquinoline-1,3(2H)-dione (named as NAOZ) and 2-(2-ethylhexyl)-6-(2-(4-(5-phenyl-1,3,4-thiadiazol-2-yl)benzylidene)hydrazinyl)-1H-benzo[*de*]isoquinoline-1,3(2H)-dione (named as NATZ), containing hydrazone and thiadiazole/oxadiazole, were successfully synthesized. Compounds NAOZ and NATZ were further used as reusable colorimetric and fluorescent chemosensors for fluoride ion. The strategies for the design of compounds NAOZ and NATZ were investigated in terms of three aspects. (1) 1,8-Naphthalimide and thiadiazole/oxadiazole moieties act as fluorophoresy. (2) Fluoride ion can deprotonate the hydrazone moiety because fluoride ion can serve as a sufficient base, leading to the observed long-wavelength color change. (3) The changes in the color of compounds NAOZ and NATZ in the presence of fluoride ion can be reversed under atmospheric carbon dioxide (CO_2).

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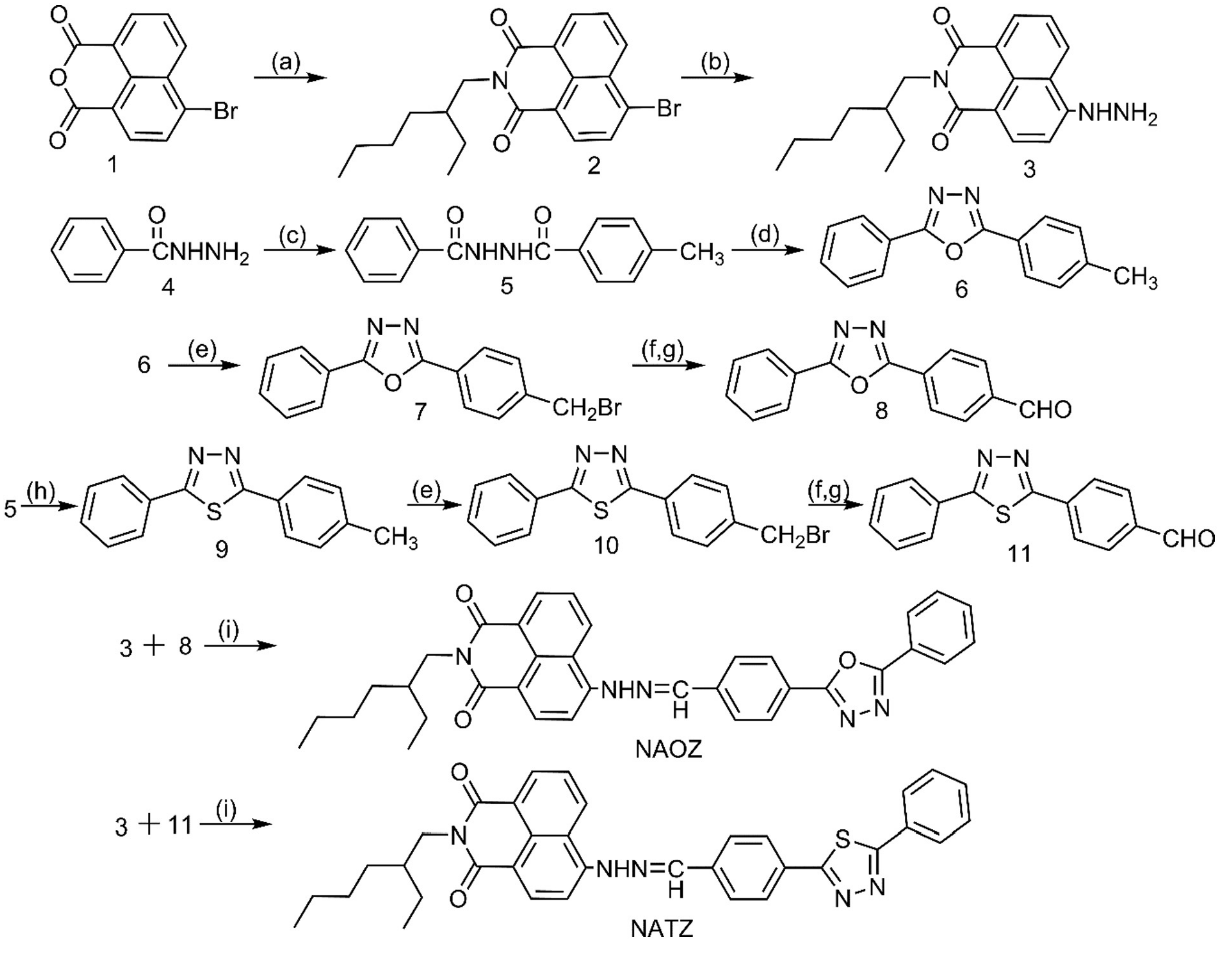
2. Results and discussion

Scheme 1 depicts the synthetic procedure for the preparation of compounds NAOZ and NATZ. Compounds 3, 8, and 11 were synthesized in accordance with previously described methods [46,47]. Compounds NAOZ and NATZ were produced by reacting one equivalent of compound 3 in 2-methoxyethanol at 100 °C with compound 8 or 11. Subsequently, compounds NAOZ and NATZ were obtained as orange powders with 65% and 61% yields through recrystallization from chloroform/ethanol.

Compounds NAOZ and NATZ can take advantage of the charge transfer (CT) character of fluorophore. As shown in Fig. S7-S10, the UV/vis absorption and emission wavelengths of compounds NAOZ and NATZ are red-shifted with the increase of the polarity of the solvent from toluene, to chloroform, to dimethyl sulfoxide (DMSO). Thus, the CT state of compounds NAOZ and NATZ may be modulated by fluoride ion through the strong deprotonation of or hydrogen bonding to the electron-donating amino moiety, thereby altering the photophysical properties of compounds NAOZ and NATZ in the presence of fluoride ion. We initially investigated these possibilities by observing the changes in the UV/vis spectra of compounds NAOZ and NATZ upon the addition of F^-, Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts. In Fig. 1a, the change in the color of the DMSO solution of compound NAOZ upon the addition of F^-, Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts (20 equiv) can be clearly observed by the naked eyes. The color of the DMSO solution of compound NAOZ is green in the absence (blank) and presence of eight anions (Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^-). The color of the DMSO solution of compound NAOZ is light blue in the presence of fluoride ion, suggesting that compound NAOZ can be used as a colorimetric chemosensor for fluoride ion. Fig. 1b displays the UV–vis absorption spectra of the DMSO solution of compound NAOZ in the absence (blank) and presence of nine anions (F^-, Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts (20 equiv). The CT absorption intensity at λ_{max} 462 nm dramatically decreases upon the addition of F^-, and two red-shifted bands at λ_{max} 615 and 652 nm appear. The bathochromic shift is as high as 190 nm. The large bathochromic shift is necessary to develop excellent fluoride ion sensors, which are used as naked eye colorimetric sensors. Under the same conditions, no evident change occurs upon the addition of eight other anions, suggesting that compound NAOZ exhibits the highest selectivity for the fluoride ion among the eight other anions. The two bands at λ_{max} 615 and 652 nm are attributed to the variations in CT because of the occurrence of a strong interaction between fluoride ion and hydrazone moiety. The titration absorption spectra of the DMSO solution of compound NAOZ with the addition of different amounts of fluoride ion are examined to verify the interaction between fluoride ion and hydrazone moiety. Fig. 1c/d and Fig. S11 shows that the CT absorption intensity at λ_{max} 462 nm decreases and becomes slightly red shifted to 464 nm as the fluoride ion concentration increases. The absorption intensities at λ_{max} 615 and 652 nm steadily increase. As shown in Fig. S12–S14, the change in color can be recovered a little due to absorption CO_2 from the air, suggesting that such sensor may be reused by adding CO_2 atmosphere. As shown in Fig. S17, the absorption behavior of the DMSO solution of compound NATZ in the absence (blank) and presence of nine anions is similar to that of the DMSO solution of compound NAOZ. Fig. S18 and S19



Scheme 1. Synthesis of compounds NAOZ and NATZ: (a) 2-ethylhexylamine, ethanol; (b) 85% hydrazine hydrate, 2-methoxyethanol; (c) 4-methylbenzoyl chloride, anhydrous triethylamine and tetrahydrofuran; (d) phosphorus oxychloride; (e) *N*-bromosuccinimide, benzoyl peroxide, anhydrous tetrachloromethane; (f) hexamethylenetetramine, chloroform; (g) glacial acetic acid; (h) Lawesson's Reagent, toluene; (i) 2-methoxyethanol.

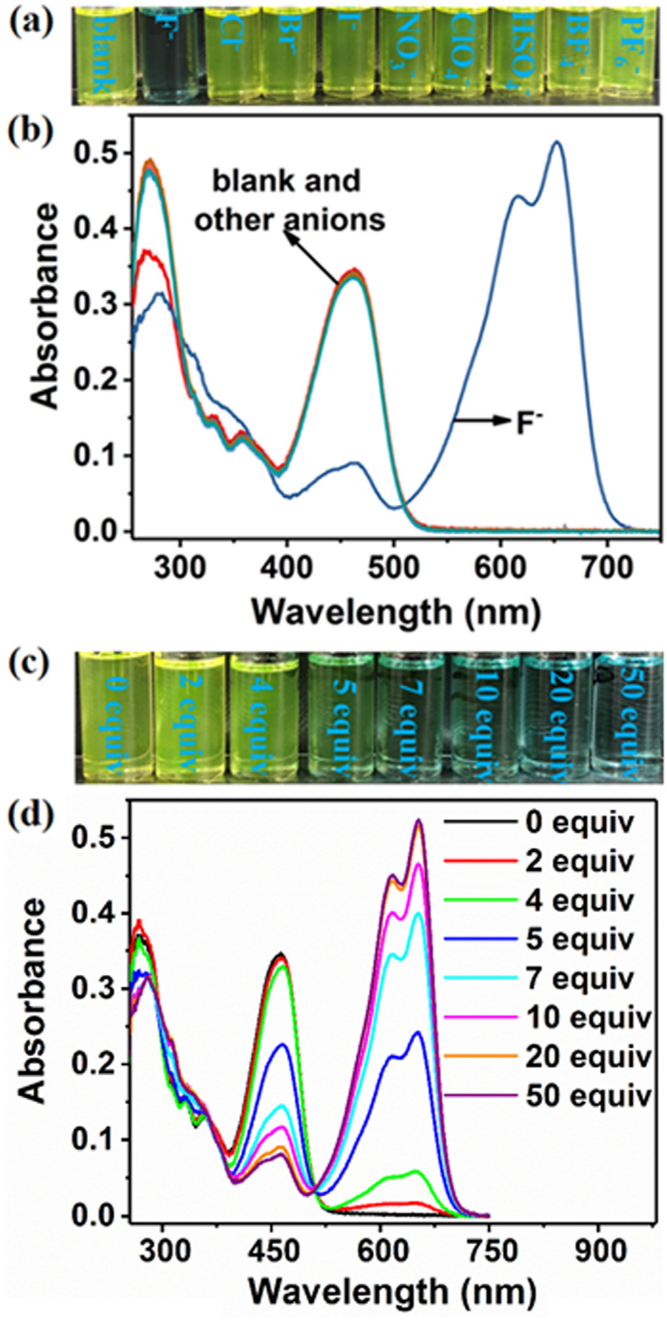


Fig. 1. (a) Change in the color of the DMSO solutions of compound NAOZ observed upon the addition of F^-, Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts (20 equiv) ([NAOZ] 10^{-5} mol L^{-1}). (b) UV/Vis absorption spectra of the DMSO solution of compound NAOZ upon the addition of F^-, Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts (20 equiv) ([NAOZ] 10^{-5} mol L^{-1}). (c) Change in the color of the DMSO solutions of compound NAOZ observed upon the addition of different amounts of F^- as its $(C_4H_9)_4N^+$ salt ([NAOZ] 10^{-5} mol L^{-1}). (d) UV/Vis absorption spectra of DMSO solutions of compound NAOZ with different amounts of F^- as its $(C_4H_9)_4N^+$ salt ([NAOZ] 10^{-5} mol L^{-1}).

exhibit that the CT absorption intensity of the DMSO solution of compound NATZ at λ_{max} 462 nm dramatically decreases upon the addition of F^-, and two red-shifted bands at λ_{max} 618 and 658 nm appear. Observing with the naked eyes is better when the bathochromic shift is larger. Although the CT absorption of compound NAOZ is the same as that of NATZ, the absorption of compound NATZ + F^- is slightly red shifted because of the lower ionization potential of the heavier chalcogen atoms compared with that of compound NAOZ + F^-.

The fluorescence emission behavior of the DMSO solutions of compound NAOZ in the absence (blank) and presence of- nine anions (F^-, Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^- as their $(C_4H_9)_4N^+$ salts (20 equiv)) is also investigated to confirm that compound NAOZ can be used as a fluorescent chemosensor for fluoride ion. In Fig. 2a/b, the photoluminescence (PL) intensity (λ_{ex} = 462 nm) of the DMSO solution of compound NAOZ is dramatically quenched in the presence of fluoride ion (20 equiv), whereas no evident fluorescence change occurs in the presence of the eight other anions, indicating that compound NAOZ can be used as a fluorescent chemosensor for fluoride ion. Fig. 2c/d shows the titration emission spectra of the DMSO solution of compound NAOZ with the addition of different amounts of fluoride ion. The PL intensity of the DMSO solution of compound NAOZ at λ_{max} 533 nm is almost quenched in the presence of 50 equiv. fluoride ion. As shown in Fig. S23 and S24, the emission behavior of the DMSO solution of compound NATZ in the absence (blank) and presence of fluoride ion is similar to that of the DMSO solution of compound NAOZ.

The interaction between compound NAOZ and F^- is investigated by the titration of the proton NMR spectra of NAOZ upon the addition of different amounts of F^- as its $(C_4H_9)_4N^+$ salt. Fig. 3 and Fig. S27 show that the proton signal of N—H proton at 11.81 disappeared upon addition of 1 equiv. F^- as its $(C_4H_9)_4N^+$ salt. Subsequently, a new proton signal at 16.59 (triplet) appears upon addition of excess F^- as its $(C_4H_9)_4N^+$ salt. Such results suggest that compound NAOZ interacts with F^- through hydrogen bonding at lower concentration of F^-. When excess F^- leads to the deprotonation of the N—H proton (Scheme S1). To get better understanding of interaction between compound NAOZ and F^-, the hybrid density functional theory (B3LYP) with 6-31G* basis set using the Gaussian 03 program package was performed. As shown in Fig. 4, the highest occupied molecular orbital (HOMO) of NAOZ is a π orbital and the electron density is distributed on the whole molecular backbone except the terminated benzene ring, while the lowest unoccupied molecular orbital (LUMO) is of π* character and the electron density is the similar to that of the HOMO. However, for NAOZ + F^-, the electron density distributions change significantly between HOMO and LUMO, suggesting strong charge transfer nature, which is consistent with the experimental results.

Although numerous colorimetric and fluorescent chemosensors for fluoride ion have been developed, the development of reusable colorimetric and fluorescent chemosensors for fluoride ion has been rarely investigated. When CO_2 is passed to the DMSO solution of compound NAOZ + F^-, the change in color and fluorescence can almost be recovered because CO_2 can react with a small amount of water to form acids, which can provide protons. To confirm this hypothesis, small amount (0.5%, v/v) of hydrochloric acid (pH = 1.5) was used to instead of CO_2. As shown in Fig. S41 and S42, the change in color and fluorescence can be easily recovered by adding small amount (0.5%, v/v) of hydrochloric acid (pH = 1.5). In Fig. 5a, the CT absorption intensity at λ_{max} 462 nm can be recovered, and the absorption intensities at λ_{max} 615 and 652 nm for the DMSO solution of compound NAOZ + F^- dramatically decrease. This phenomenon is confirmed by the fluorescence spectra (Fig. 5b). The PL intensity of the DMSO solution of compound NAOZ + F^- is almost recovered by passing CO_2 to the DMSO solution of compound NAOZ + F^-, suggesting that compound NAOZ can be used as a recyclable colorimetric and fluorescent chemosensor for fluoride ion.

3. Conclusions

In summary, two reusable colorimetric and fluorescent chemosensors (compounds NAOZ and NATZ) for fluoride ion are successfully synthesized. Compounds NAOZ and NATZ can act as an efficient anion sensor for fluoride ion over a wide range of other anions (Cl^-, Br^-, I^-, NO_3^-, ClO_4^-, HSO_4^-, BF_4^-, and PF_6^-) because fluoride ion can deprotonate the hydrazone moiety, leading to the observed

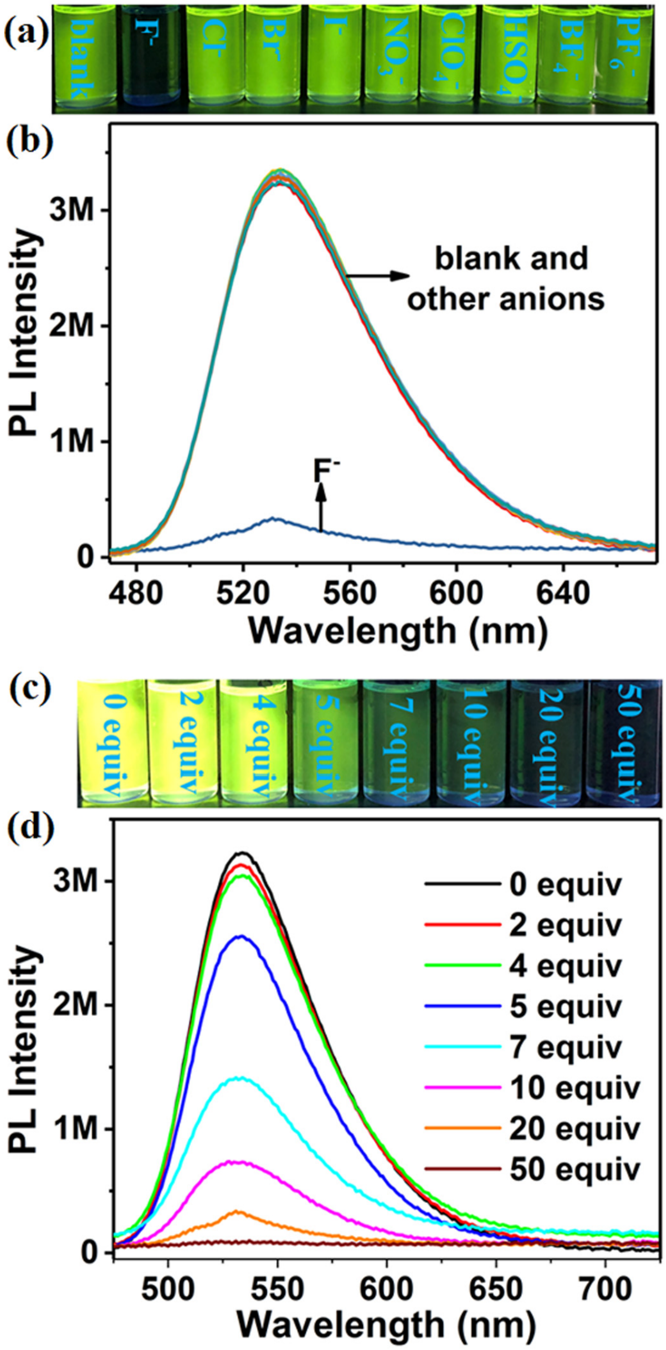


Fig. 2. (a) Photographs of DMSO solutions of compound NAOZ observed upon the addition of F$^-$, Cl$^-$, Br$^-$, I$^-$, NO$_3^-$, ClO$_4^-$, HSO$_4^-$, BF$_4^-$, and PF$_6^-$ as their $(C_4H_9)_4N^+$ salts (20 equiv) under UV light at 365 nm ([NAOZ] 10^{-5} mol L^{-1}). (b) Emission spectra of the DMSO solutions of compound NAOZ observed upon the addition of F$^-$, Cl$^-$, Br$^-$, I$^-$, NO$_3^-$, ClO$_4^-$, HSO$_4^-$, BF$_4^-$, and PF$_6^-$ as their $(C_4H_9)_4N^+$ salts (20 equiv). Excitation wavelength = 462 nm ([NAOZ] 10^{-5} mol L^{-1}). (c) Photographs of the DMSO solutions of compound NAOZ with different amounts of F$^-$ as its $(C_4H_9)_4N^+$ salt ([NAOZ] 10^{-5} mol L^{-1}). (d) Emission spectra of DMSO solutions of compound NAOZ with different amounts of F$^-$ as its $(C_4H_9)_4N^+$ salt. Excitation wavelength = 462 nm ([NAOZ] 10^{-5} mol L^{-1}).

long-wavelength color change. The CT absorption peak of the DMSO solution of compound NATZ at λ_{max} 462 nm is dramatically red shifted at 197 nm upon the addition of F$^-$. Observing with the naked eyes is better when the bathochromic shift is larger. Interestingly, CO$_2$ can recover the CT absorption and PL intensities of compound NAOZ/NATZ + F$^-$ because CO$_2$ can react with a small amount of water to form acids, which can provide protons. Our results suggest that the introduction of hydrazone and thiadiazole/oxadiazole groups to the 1,8-naphthalimide backbone can improve the performance in detecting fluoride ion. We will introduce water-soluble groups such as poly(ethylene glycol) methyl ether into start materials to improve the solubility of target compounds in water in our future work.

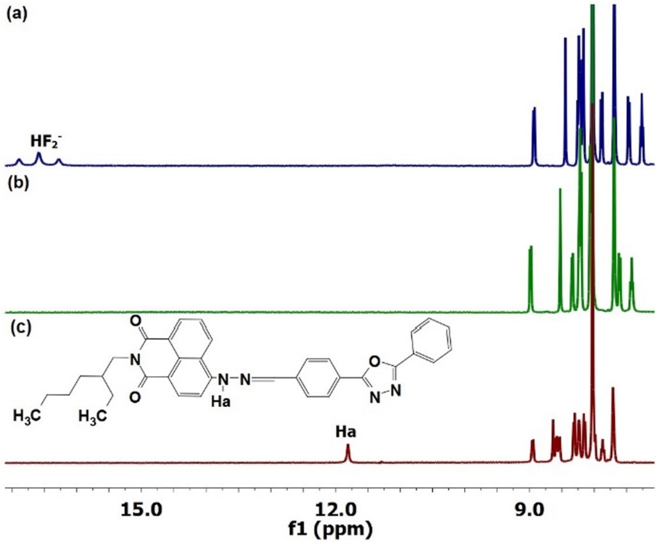


Fig. 3. The titration of the proton NMR spectra of NAOZ upon the addition of different amounts of F$^-$ as its $(C_4H_9)_4N^+$ salt (a. 1 equiv. of F$^-$; b. 4 equiv. of F$^-$; c. pure compound NAOZ) in DMF-d$_7$.

CRediT authorship contribution statement

Liang Zhang: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision. **Feng Zhang:** Writing - review & editing. **Liang Ding:** Writing - review & editing. **Junkuo Gao:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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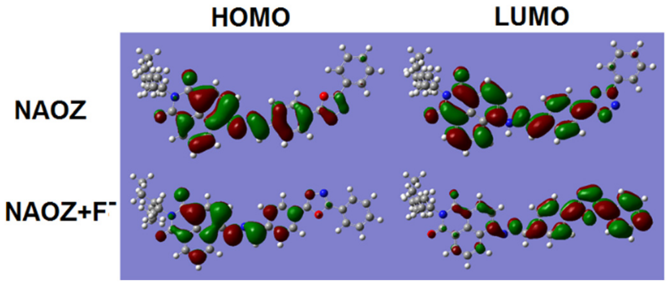

Fig. 4. Calculated spatial distributions of the HOMO and LUMO levels of compound NAOZ and NAOZ + F$^-$.

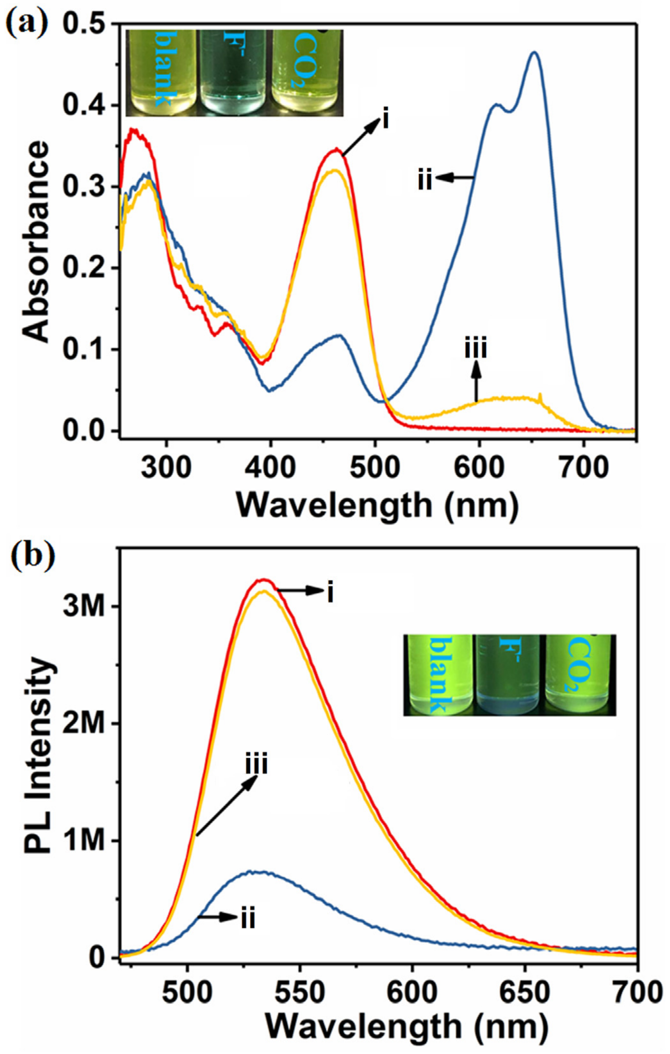

Fig. 5. (a) UV/Vis absorption spectra of the DMSO solutions of compound NAOZ in the absence (blank, i) and presence of F^- as its $(C_4H_9)_4N^+$ salts (10 equiv., ii) and CO_2 atmosphere (iii, [NAOZ] 10^{-5} mol L^{-1}). Inset: Photograph from left to right presents the change in the color of the absence (blank) and presence of F^- as its $(C_4H_9)_4N^+$ salts (10 equiv) and CO_2 atmosphere. (b) Emission spectra of the DMSO solutions of compound NAOZ in the absence (blank, i) and presence of F^- as its $(C_4H_9)_4N^+$ salts (10 equiv., ii) and CO_2 atmosphere (iii, [NAOZ] 10^{-5} mol L^{-1}). Excitation wavelength = 462 nm. Inset: Photograph from left to right shows the change in the color of the absence (blank) and presence of F^- as its $(C_4H_9)_4N^+$ salts (10 equiv) and CO_2 atmosphere under UV light at 365 nm.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.saa.2020.118395.

References

[1] Y. Zhou, J.F. Zhang, J. Yoon, Fluorescence and colorimetric chemosensors for chloride-ion detection, Chem. Rev. 114 (2014) 5511–5571.
[2] B. Chen, L. Wang, F. Zapata, G. Qian, E.B. Lobkovsky, A luminescent microporous metal-organic framework for the recognition and sensing of anions, J. Am. Chem. Soc. 130 (2008) 6718–6719.
[3] S. Nishizawa, Y. Kato, N. Teramae, Fluorescence sensing of anions via intramolecular excimer formation in a pyrophosphate-induced self-assembly of a pyrene-functionalized guanidinium receptor, J. Am. Chem. Soc. 121 (1999) 9463–9464.
[4] T. Gunnlaugsson, A.P. Davis, M. Glynn, Fluorescent photoinduced electron transfer (PET) sensing of anions using charge neutral chemosensors, Chem. Commun. (2001) 2556–2557.
[5] G.Q. Fang, H. Wang, Z.C. Bian, J. Sun J, A.Q. Liu, H. Fang, B. Liu, Q.Q. Yao, Z.Y. Wu, Recent development of boronic acid-based fluorescent sensors, RSC Adv. 8 (2018) 29400–29427.
[6] J.P. Leonard, C.M.G. dos Santos, S.E. Plush, T. McCabe, T. Gunnlaugsson, pH driven self-assembly of a ternary lanthanide luminescence complex: the sensing of anions using a b-diketonate-Eu(III) displacement assay, Chem. Commun. (2007) 129–131.
[7] T.G. Levitskaia, S. Chatterjee, B.W. Arey, E.L. Campbell, Y.C. Hong, L. Kovarik, J.M. Peterson, N.K. Pence, J. Romero, V. Shutthanandan, B. Schwenzer, T. Varga, RedOx-controlled sorption of iodine anions by hydrotalcite composites, RSC Adv. 6 (2016) 76042–76055.
[8] Q.T. Meng, Y. Wang, H. Feng, F. Zhou, B. Zhou, C.P. Wang, R. Zhang, Z.Q. Zhang, A novel glucosamine-linked fluorescent chemosensor for the detection of pyrophosphate in an aqueous medium and live cells, New J. Chem. 42 (2018) 2675–2681.
[9] J. Zhao, J.I. Wong, C. Wang, J. Gao, V.Z.Y. Ng, H.Y. Yang, S.C.J. Loo, Q. Zhang, Synthesis, physical properties, and self-assembly of a novel asymmetric aroyleneimidazophenazine, Chem. Asian J. 8 (2013) 665–669.
[10] B. Gu, Q. Zhang, Recent advances on functionalized upconversion nanoparticles for detection of small molecules and ions in biosystems, Adv. Sci. 5 (2018) 1700609–1700624.
[11] P.-Y. Gu, Z. Wang, Q. Zhang, Azaacenes as active elements for sensing and bio applications, J. Mater. Chem. B 4 (2016) 7060–7074.
[12] Y. Zhou, W. Pei, C. Wang, J. Zhu, J. Wu, Q. Yan, L. Huang, W. Huang, C. Yao, J.S.C. Loo, Q. Zhang, Rhodamine-modified upconversion nanophosphors for ratiometric detection of hypochlorous acid in aqueous solution and living cells, Small 10 (2014) 3560–3567.
[13] C. Wang, G. Li, Q. Zhang, A novel heteroacene, 2-(2, 3, 4, 5-tetrafluorophenyl)-1H-imidazo [4, 5-b] phenazine as a multi-response sensor for F— detection, Tetrahedron Lett. 54 (2013) 2633–2636.
[14] L. Xu, Y. Li, Y. Yu, T. Liu, S. Cheng, H. Liu, Y. Li, A receptor incorporating OH, NH and CH binding motifs for a fluoride selective chemosensor, Org. Biomol. Chem. 10 (2012) 4375–4380.
[15] C.R. Wade, A.E.J. Broomsgrove, S. Aldridge, F.P. Gabbaï, Fluoride ion complexation and sensing using organoboron compounds, Chem. Rev. 110 (2010) 3958–3984.
[16] X.W. Xu, Y.Q. Chen, L. Wei, W.X. Mao, F. Lin, X. Zhou, Fluorescent turn-on probes for the detection of fluoride ions in organic solvent and in cells, Anal. Methods 8 (2016) 245–248.
[17] R. Hu, J. Feng, D. Hu, S. Wang, S. Li, Y. Li, G. Yang, A rapid aqueous fluoride ion sensor with dual output modes, Angew. Chem. Int. Ed. 49 (2010) 4915–4918.
[18] Y. You, S.Y. Park, A phosphorescent Ir(III) complex for selective fluoride ion sensing with a high signal-to-noise ratio, Adv. Mater. 20 (2008) 3820–3826.
[19] I.H.A. Badr, M.E. Meyerhoff, Highly selective optical fluoride ion sensor with submicromolar detection limit based on aluminum(III) octaethylporphyrin in thin polymeric film, J. Am. Chem. Soc. 127 (2005) 5318–5319.
[20] D.E. Gómez, L.G. Fabbrizzi, M. Licchelli, E. Monzani E, Urea vs. thiourea in anion recognition, Org. Biomol. Chem 3 (2005) 1495–1500.
[21] S.Y. Gwon, S.H. Kim, Anion sensing and F(—)-induced reversible photoreaction of D-pi-A type dye containing imidazole moiety as donor, Spectrochim. Acta A 117 (2014) 810–813.
[22] S.M. Basheer, M. Muralisankar, T.V. Anjana, K.N. Aneesrahman, A. Sreekanth, Multi-ion detection and molecular switching behaviour of reversible dual fluorescent sensor, Spectrochim. Acta A 182 (2017) 95–104.
[23] L. Zhang, F. Liu, Synthesis of bisimidazole derivatives for selective sensing of fluoride ion, Molecules 22 (2017) 1519.
[24] K. Ghosh, S. Adhikari, Colorimetric and fluorescence sensing of anions using thiourea based coumarin receptors, Tetrahedron Lett. 47 (2006) 8165–8169.
[25] R. Li, S. Wang, Q. Li, H. Lan, S. Xiao, Y. Li, R. Tan, T. Yi, A fluorescent non-conventional organogelator with gelation-assisted piezochromic and fluoride-sensing properties, Dyes Pigments 137 (2017) 111–116.
[26] L. Xu, H. Zhu, G. Long, J. Zhao, D. Li, R. Ganguly, Y. Li, Q.-H. Xu, Q. Zhang, 4-Diphenylamino-phenyl substituted pyrazine: nonlinear optical switching by protonation, J. Mater. Chem. C 3 (2015) 9191–9196.
[27] S. Yamaguchi, S. Akiyama, K. Tamao, Colorimetric fluoride ion sensing by boron-containing π-electron systems, J. Am. Chem. Soc. 123 (2001) 11372–11375.
[28] Y.H. Zhou, X.L. Dong, Y.X. Zhang, P. Tong, J.P. Qu, Highly selective fluorescence sensors for the fluoride anion based on carboxylate-bridged diiron complexes, Dalton Trans. 45 (2016) 6839–6846.
[29] Y. Kubo, M. Yamamoto, M. Ikeda, M. Takeuchi, S. Shinkai, S. Yamaguchi, K. Tamao, A colorimetric and ratiometric fluorescent chemosensor with three emission changes: fluoride ion sensing by a triarylborane–porphyrin conjugate, Angew. Chem. Int. Ed. 42 (2003) 2036–2040.
[30] S. Guha, S. Saha, Fluoride ion sensing by an anion-π interaction, J. Am. Chem. Soc. 132 (2010) 17674–17677.
[31] Y.Q. Zheng, Y.D. Duan, K.L. Ji, R.L. Wang, B.H. Wang, Tuning the reaction rates of fluoride probes for detection in aqueous solution, RSC Adv. 6 (2016) 25242–25245.
[32] J. Wang, X. Qian, Two regioisomeric and exclusively selective Hg(II) sensor molecules composed of a naphthalimide fluorophore and an o-phenylenediamine derived triamide receptor, Chem. Commun. (2006) 109–111.
[33] X. Qian, Y. Xiao, Y. Xu, X. Guo, J. Qian, W. Zhu, "Alive" dyes as fluorescent sensors: fluorophore, mechanism, receptor and images in living cells, Chem. Commun. 46 (2010) 6418–6436.
[34] M. Havlík, V. Talianová, R. Kaplánek, T. Bříza, B. Dolenský, J. Králová, P. Martásek, V. Král, Versatile fluorophores for bioimaging applications: π-expanded naphthalimide derivatives with skeletal and appendage diversity, Chem. Commun. 55 (2019) 2696–2699.
[35] L.Y. Chen, S.J. Park, D. Wu, H.M. Kim, J.Y. Yoon, A two-photon fluorescent probe for colorimetric and ratiometric monitoring of mercury in live cells and tissues, Chem. Commun. 55 (2019) 1766–1769.

[36] S. Chen, P.J. Zeng, W.G. Wang, X.D. Wang, Y.K. Wu, P.J. Lin, Z.C. Peng, Naphthalimide–arylamine derivatives with aggregation induced delayed fluorescence for realizing efficient green to red electroluminescence, J. Mater. Chem. C 7 (2019) 2886–2897.

[37] R.M. Duke, E.B. Veale, F.M. Pfeffer, P.E. Kruger, T. Gunnlaugsson, Colorimetric and fluorescent anion sensors: an overview of recent developments in the use of 1,8-naphthalimide-based chemosensors, Chem. Soc. Rev. 39 (2010) 3936–3953.

[38] R.M. Duke, T. Gunnlaugsson, 3-Urea-1,8-naphthalimides are good chemosensors: a highly selective dual colorimetric and fluorescent ICT based anion sensor for fluoride, Tetrahedron Lett. 52 (2011) 1503–1505.

[39] H.D.P. Ali, P.E. Kruger, T. Gunnlaugsson, Colorimetric 'naked-eye' and fluorescent sensors for anions based on amidourea functionalised 1,8-naphthalimide structures: anion recognition via either deprotonation or hydrogen bonding in DMSO, New J. Chem. 32 (2008) 1153–1161.

[40] E.B. Veale, G.M. Tocci, F.M. Pfeffer, P.E. Kruger, T. Gunnlaugsson, Demonstration of bidirectional photoinduced electron transfer (PET) sensing in 4-amino-1,8-naphthalimide based thiourea anion sensors, Org. Biomol. Chem 7 (2009) 3447–3454.

[41] J. Ren, Z. Wu, Y. Zhou, Y. Li, Z. Xu, Colorimetric fluoride sensor based on 1,8-naphthalimide derivatives, Dyes Pigments 91 (2011) 442–445.

[42] T.S. Reddy, R. Maragani, R. Misra, Triarylborane substituted naphthalimide as a fluoride and cyanide ion sensor, Dalton Trans. 45 (2016) 2549–2553.

[43] C. Pati, K. Ghosh, A 1,8-naphthalimide–pyridoxal conjugate as a supramolecular gelator for colorimetric read out of F— ions in solution, gel and solid states, New J. Chem. 43 (2019) 2718–2725.

[44] G.J. Ye, T.T. Zhao, Z.N. Jin, P.Y. Gu, J.Y. Mao, Q.H. Xu, Q.F. Xu, J.M. Lu, N.J. Li, Y.L. Song, The synthesis and NLO properties of 1,8-naphthalimide derivatives for both femtosecond and nanosecond laser pulses, Dyes Pigments 94 (2012) 271–277.

[45] P.Y. Gu, X.F. Xu, F. Zhou, T.T. Zhao, G.J. Ye, G.Y. Liu, Q.H. Xu, J.F. Ge, Q.F. Xu, J.M. Lu, Study of linear and nonlinear optical properties of four derivatives of substituted aryl hydrazones of 1,8-naphthalimide, Chin. J. Chem. 32 (2014) 205–211.

[46] P.Y. Gu, C.J. Lu, Z.J. Hu, N.J. Li, T.T. Zhao, Q.F. Xu, Q.H. Xu, J.D. Zhang, J.M. Lu, The AIEE effect and two-photon absorption (TPA) enhancement induced by polymerization: synthesis of a monomer with ICT and AIE effects and its homopolymer by ATRP and a study of their photophysical properties, J. Mater. Chem. C 1 (2013) 2599–2606.

[47] P.Y. Gu, J. Gao, Q. Zhang, G. Liu, F. Zhou, Q.F. Xu, J.M. Lu, Tuning optical properties of phenanthroline derivatives through varying excitation wavelength and pH values, J. Mater. Chem. C 2 (2014) 1539–1544.