

# A pyrenyl-appended $C_{3v}$ -symmetric homooxacalix[3]arene for selective fluorescence sensing of iodide

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**ABSTRACT:** A new  $C_{3v}$ -symmetric homooxacalix[3]arene **L** bearing pyrene moieties as fluorophore has been designed and synthesized. **L** exhibits a significant fluorescence quenching responses to  $I^-$  even in the concurrent presence of other potentially competing anions. There is a good linear relationship between the fluorescence intensity and the concentration of  $I^-$  ranging from 0 to 100  $\mu$ M and the detection limit was calculated to be as low as 164 nM. The ligand **L** can be served as fluorescent chemosensor for highly selective, sensitive, and rapid detection of  $I^-$ .  
**Keywords:** Homooxacalix[3]arene, Fluorescent chemosensor, Pyrene, Amide, Iodide ( $I^-$ )

## 1. Introduction

Iodine as a basic micronutrient, plays a fundamental physiological role in all stages of human development [1,2]. Improper intake of iodine remains a major concern in public health, because either a deficiency or an overabundance of iodine was associated with adverse health consequences. For example, iodine deficiency causes several diseases such as goiter and cretinism, while excessive ingestion of iodine contributes to certain thyroid diseases including hyperthyroidism and hypothyroidism[3,4]. Therefore, the development of highly sensitive and selective analytical methodology for the detection of trace levels of iodide is highly demanded and of great significance.

Till date, several analytical methods have been reported for the determination of iodide, such as atomic absorption spectrometry[5], microfluidic flow injection [6], colorimetry [7,8], capillary electrophoresis [9], electrochemical analysis [10,11],

chromatography [12,13], mass spectrometry[14,15] and so on. However, these methods still suffer from some intrinsic disadvantages, including tedious sample preparations, time-consuming operation and sophisticated instrumentation. Besides that, the interference of coexisting anions seriously affected the performance of some techniques and these methods have the difficulty for the detection of iodide in some real samples like urine. Particularly, fluorescence methodology has been widely used as a great tool for detection of ion species due to its operational simplicity, high sensitivity and selectivity [16-18]. In recent years a number of selective fluorescent sensors have been developed for the detection of iodide ion by the change in photophysical or colorimetric properties of the receptor without substantial interferences from other anions [19-23].

Homooxacalix[3]arenes are related to both calixarenes and crown ethers, and possess a three-dimensional cavity with a  $C_{3v}$  symmetric structure. Importantly,

homooxacalix[ $n$ ]arenes incorporate extra ethereal linkages which makes them relatively flexible and thus they can provide a suitable binding environment for species that require trigonal-planar, tetrahedral, or octahedral coordination [24-26]. Based on this excellent structural versatility, homooxacalix[ $n$ ]arenes exhibit characteristic affinities for metal cations [27,28], ammonium cations [29,30], anions [31,32] and fullerene derivatives [33,34]. However, homooxacalix[3]arenes has been scarcely exploited for the design of anions receptors. Recently, Marcos and co-workers reported a dihomooxacalix[4]arene-gold nanohybrid based colorimetric sensor for sensitive and selective detection of iodide with a detection limit of 8.3 nM and almost no interference from other anions [35]. Thus, the application of homooxacalix[3]arene molecular platform offers great potential for development of receptors in the molecular recognition of iodide. In the present manuscript, we report a pyrenyl-appended  $C_{3v}$ -symmetric homooxacalix[3]arene **L**, which was found to be

a selective fluorescence chemosensor for  $I^-$  with little interference from the other anions studied.

## 2. Experimental

### 2.1. General

Unless otherwise stated, all reagents used were purchased from commercial sources and were used without further purification. All the solvents used were dried and distilled by the usual procedures before use. All melting points were determined using a Yanagimoto MP-S1.  $^1H$  NMR and  $^{13}C$  NMR spectra were recorded on a Nippon Denshi JEOL FT-300 NMR spectrometer and a Varian-400MRvnmrs400 with  $SiMe_4$  as an internal reference:  $J$ -values are given in Hz. IR spectra were measured as KBr pellets or as liquid films on NaCl plates in a Nippon Denshi JIR-AQ2OM spectrophotometer. UV spectra were measured by a Shimadzu UV-3150UV-vis-NIR spectrophotometer. Fluorescence spectroscopic studies of compounds in solution were performed in a semi-micro fluorescence cell (Hellma®, 104F-QS, 10 × 4 mm, 1400  $\mu$ L) with a Varian Cary Eclipse spectrophotometer. Mass spectra were obtained on a Nippon Denshi JMS-01SG-2 mass spectrometer at an ionization energy of 70 eV using a direct inlet system through GLC. Elemental analyses were performed by a Yanaco MT-5.

### 2.2. Synthesis

Compounds **2** [36] and **3** [37] were prepared following the reported procedures.

#### 2.2.1 General procedure for synthesis of compound **2**.

A mixture of **1** (500 mg, 0.87 mmol) and NaH (210 mg, 5.22 mmol) in dry THF (25 mL) was heated at reflux for 1 h under N<sub>2</sub>. Then *N,N*-diethylchloroacetamide (780 mg, 5.22 mmol) was added and the mixture was heated at reflux for additional 20 h. After cooling to room temperature, the mixture was filtered. The filtrate was concentrated to give a yellow oil, which was recrystallized from methanol gave **2** (540 mg, 68 %) as colorless powder. M.p. 215–217 °C. <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ = 1.08 (s, 27H, t-Bu), 1.13 and 1.16 (t each, 9H each, CH<sub>3</sub>), 3.34 and 3.38 (q each, 6H each, NCH<sub>2</sub>), 4.57 (s, 6H, OCH<sub>2</sub>CO), 4.62 and 4.93 (d each, 6H each, ArCH<sub>2</sub>O), 6.98 (s, 6H, ArH).

#### 2.2.3 General procedure for synthesis of compound **3**.

Aqueous NaOH solution (1 N, 20 mL) was added to a mixture of **2** (1.0 g, 1.09 mmol) in dioxane (20 mL). After the mixture had been refluxed for three days, it was condensed under reduced pressure, then acidified to pH 1-2. The organic layer was extracted with ethyl acetate (2 × 30 mL). The combined extracts were washed with water (2 × 20 mL) and saturated brine (20 mL), dried (Na<sub>2</sub>SO<sub>4</sub>), and condensed under reduced pressure. The residue was recrystallized from methanol gave 605 mg (74 %) of compound **3** as colorless powder. M.p. 227–229 °C. <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ = 1.14 (s, 27H, tBu), 4.44 (d, 6H, ArCH<sub>2</sub>O), 4.46 (s, 6H, ArOCH<sub>2</sub>), 4.92 (d, 6H, ArCH<sub>2</sub>O), 6.95 (s, 6H, ArH). <sup>13</sup>C NMR (CDCl<sub>3</sub>/DMSO, 1:1): δ = 28.85, 31.43, 66.85, 67.90, 123.45, 128.43, 142.71, 150.35, 168.52.

#### 2.2.4 General procedure for synthesis of compound **L**.

HoBt (270 mg, 2.00 mmol) and 1-aminopyrene (582 mg, 2.68 mmol) were added to a solution of **3** (500 mg, 0.67 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (50 mL). The mixture was then stirred at 0 °C while a solution of DCC (1.24 g, 6 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (50 mL) was added dropwise. The solution was stirred for 1 h at 0 °C and for an additional 24 h at room temperature. After completion, the solvent was removed under reduced pressure. The residue was purified by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane (1:1)) to give 584 mg of **L** as a colorless solid in 65% yield. M.p. 329–330 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δ = 1.24 (s, 27H, tBu), 4.57 (d, 6H, ArCH<sub>2</sub>(eq)O, J = 9.2 Hz), 4.60 (s, 6H, ArOCH<sub>2</sub>), 5.21 (d, 6H, ArCH<sub>2</sub>(ax)O, J = 12.0 Hz), 6.89 (d, 3H, pyrene-H, J = 8.4 Hz), 7.12 (s, 6H, ArH), 7.23 (d, 3H, pyrene-H, J = 9.2 Hz), 7.33 (d, 3H, pyrene-H, J = 9.2 Hz), 7.44-7.56 (m, 12H, pyrene-H), 7.67 (d, 3H, pyrene-H, J = 6.8 Hz), 7.75 (d, 3H, pyrene-H, J = 9.2 Hz), 9.54 (s, 3H, NH). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>) δ = 31.55, 34.36, 70.69, 74.26, 119.84, 121.06, 122.89, 123.56, 123.86, 123.99, 124.18, 124.49, 125.13, 125.97, 126.35, 126.68, 128.15, 128.17, 128.87, 129.87, 130.41, 131.18, 147.29, 153.57, 168.21. HRMS *m/z* Calcd for C<sub>90</sub>H<sub>81</sub>N<sub>3</sub>O<sub>9</sub>

[M]<sup>+</sup>: 1348.6006 Found: 1348.6006 [M]<sup>+</sup>.

#### 2.3 General procedure for the fluorescence titrations

For fluorescence measurements, compound **L** were dissolved in THF to obtain stock solutions (1 mM). The stock solutions were diluted with THF to afford the desired concentration. Stock solutions ( $10^{-3}$  M) of sodium salts ( $F^-$ ,  $Cl^-$ ,  $Br^-$ ,  $I^-$ ,  $AcO^-$ ,  $SO_3^{2-}$ ,  $SO_4^{2-}$ ,  $HSO_3^-$ ,  $NO_3^-$  and  $CO_3^{2-}$ ) were prepared with water. In titration experiments, typically, aliquots of freshly prepared standard solutions ( $10^{-3}$  M to  $10^{-6}$  M) of various analytes in water were added to record the fluorescence spectra. The fluorescence spectra were performed with the excitation wavelength 346 nm.

### 3. Results and discussion

#### 3.1. Synthesis and structure

##### Insert Scheme 1 in here

From a structural viewpoint, the  $C_{3v}$ -symmetric structure with multiple binding sites has the ability to form spheroidal cavities to encapsulate anions of perfect fitting, thus the  $C_{3v}$ -symmetric tripodal anion receptors have shown highly effective anion recognition ability [38]. On the other hand, amides had been widely exploited as hydrogen bond groups for binding anions [39]. Therefore, we hypothesized that suitably arranged functionalized ligand moieties containing amides attached to homooxalix[3]arene should be a good receptor candidate for iodide ions. With this in mind, we have synthesized the  $C_{3v}$ -symmetric homooxalix[3]arene **L** and studied its anion-binding affinity.

The fluorescent ligand **L** was prepared by a condensation reaction of triacid **3** with 4.0 mol equiv. of 1-aminopyrene in the presence of 1-hydroxybenzotriazole (HoBt, 2.0 mol equiv.) and dicyclohexylcarbodiimide (DCC, 9.0 mol equiv.) at room temperature for 24 h in  $CH_2Cl_2$  with a 65% yield. Conformation assignments for the new homooxalix[3]arene triamide derivative **L** was firmly established by its NMR spectra. The  $^1H$  NMR spectrum showed one singlet at  $\delta$  1.24 ppm characteristic of *tert*-butyl protons, one singlet at  $\delta$  4.60 ppm for  $OCH_2CO$  methylene protons, and one singlet at  $\delta$  7.12 ppm for aromatic protons, one singlet at  $\delta$  9.54 ppm for the amide protons. The other peaks were observed as one pair of doublet for the  $ArCH_2O$  bridge methylene protons and a series of doublets for the pyrene groups. On the other hand, the  $^{13}C$  NMR spectrum exhibited 21 downfield resonances arising from the carbonyl and aromatic carbon atoms (four from the calixarene skeleton and sixteen from the pyrene rings), two midfield resonances arising from the methylene carbon atoms of the  $OCH_2CO$  and  $ArCH_2O$  groups, and two upfield resonances arising from the *tert*-butyl groups. Furthermore, the fast atom bombardment (FAB)-mass spectrum clearly showed the molecular ion  $[M+H]^+$  at  $m/z = 1348.6006$ . These spectral properties indicated that **L** possesses a  $C_{3v}$  symmetry. These findings reveal that the homooxalix[3]arene skeleton was immobilized in the *cone* conformation.

#### 3.2. Fluorescence Sensing Properties of **L** for $I^-$

##### Insert Fig 1 in here

The receptor **L** was good soluble in organic solvent such as THF, whereas insoluble in water. For practical applications, the fluorescence response of **L** (in THF) upon

addition of water was initially monitored (Fig. 1). The concentration of **L** was kept at 5.0  $\mu\text{M}$  in THF-water mixtures. When the water fractions ( $f_w$ ) increased from 0 to 30%, the emission intensity at 484 nm was gradually enhanced. However, when a large amount of water ( $f_w = 70\%$ ) is added to the solution in THF, the emission intensity was sharply decreased (Fig. S1). In addition, the pH stability was also checked, and was found to be considerably stable in the pH range of 2–11 (Fig. S2). According to above results, a THF-H<sub>2</sub>O (v/v = 7/3, Tris-HCl buffer, pH = 7.0) co-solvent was chosen for further experiments.

#### Insert Fig 2 in here

The investigation for the affinity of fluorescent ligand **L** towards some biologically relevant anions ( $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$ ,  $\text{AcO}^-$ ,  $\text{SO}_3^{2-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{HSO}_3^-$ ,  $\text{NO}_3^-$  and  $\text{CO}_3^{2-}$ ) was performed by quantitative fluorescence spectroscopy. Remarkably, a substantial reduction of fluorescence intensity was observed on the addition of  $\text{I}^-$  in comparison to other anions, where there was almost no quenching of fluorescence intensity under the similar conditions (Fig. 2). The fluorescence titration analysis confirms the exclusive  $\text{I}^-$ -selective recognition of receptor **L** among all other anions, showing significant quenching of intensity of the emission signal at 484 nm upon the addition of  $\text{I}^-$ . Furthermore, the response time or sensitivity is another important factor in the practical applications of a chemosensor. To check the sensitivity of **L** towards  $\text{I}^-$ , the behavior of **L** containing  $\text{I}^-$  was studied as a function of time. The change in the fluorescence spectrum was investigated after short intervals of time when 100 equiv. of  $\text{I}^-$  was added to the solution of **L**. The results showed that the fluorescence intensity was quenched immediately after the  $\text{I}^-$  addition, and after that there is no significant change in fluorescence intensity up to 100 s (Fig. S3). These results clearly demonstrated that the quenching of the fluorescence is rapid and stable, suggesting remarkable potential of **L** act as an excellent chemosensor for the fluorescence turn-off detection of  $\text{I}^-$ .

#### Insert Fig 3 in here

To further investigate the selective sensing properties of **L** towards  $\text{I}^-$ , fluorescence titration experiments were performed. As seen in Fig. 3, upon the stepwise addition of  $\text{I}^-$  to a solution of **L**, the emission intensity of **L** at 484 nm was gradually quenched. The resulting calibration curve for  $\text{I}^-$  displays distinct linearity for concentration range from 0 to 200  $\mu\text{M}$  with a correlation coefficient ( $R^2$ ) of 0.992 (Fig. S4). The detection limit for  $\text{I}^-$  is 164 nM based on the equation  $\text{LOD} = 3\sigma/K$ , where  $\sigma$  is the standard deviation for 10 blank tests and  $K$  is the slope of the calibration curve [40, 41]. To assess the potential application of **L** as an  $\text{I}^-$ -selective fluorescent chemosensor, a comparison of the sensing performance of our method with some other previous methods was listed in Table 1. Compared with other methods for  $\text{I}^-$  detection, chemosensor **L** offered a comparable detection limit and linear range.

Although the LOD of the proposed chemosensor **L** is not the lowest, the high sensitivity and selectivity and the simplicity made it a novel and important approach in the determination of  $I^-$ .

**Insert Table 1 in here**

A better view regarding the sensitivity of chemosensor **L** towards the sensing of  $I^-$  can be obtained by fitting the experimental data in the Stern–Volmer (SV) equation  $I_0/I = K_{SV}[A] + 1$ , where  $I_0$  and  $I$  are the emission intensities before and after the addition of the analyte,  $[A]$  is the molar concentration of the analyte and  $K_{SV}$  is the quenching constant. Based on the fluorescence titration results, the Stern–Volmer plot was found to be linear at lower concentrations (up to 100  $\mu$ M, Fig. S5), which indicates that fluorescence quenching involves a static quenching mechanism at lower concentrations of  $I^-$ . The quenching constant was calculated to be  $K_{SV} = 8.88 \times 10^3$   $M^{-1}$ . However, extrapolation of the plot towards higher concentration led to deviation from linearity (Fig. S6). This indicates dynamic collision via heavy atom effect which is predominating over static interaction at higher concentration range [42]. These results demonstrated the formation of the non-fluorescence groundstate complex between the chemosensor **L** and  $I^-$ .

**Insert Fig 4 in here**

For the effective and specific sensing of  $I^-$ , either minimal or no interference from other concomitant anions is an essential requirement. Competition experiments were performed by measuring the fluorescence intensities of chemosensor **L** (5  $\mu$ M) in presence of 100 equiv. of individual interfering anions and  $I^-$ . Particularly, in an attempt to mimic the in vivo situation, all interfering anions were mixed together with **L** and then  $I^-$  ion was added. As shown in Fig. 4, there was no interference observed with all the potential interferents in competition experiments, which suggested that chemosensor **L** is effective for fluorescence quenching detection of  $I^-$  even in the presence of other competing anions.

### 3.3. The proposed sensing mechanism

**Insert Fig 5 in here**

**Insert Scheme 2 in here**

To have clear idea about the mechanism of quenching taking place in the presence of  $I^-$ ,  $^1H$  NMR titration experiments were investigated. From the  $^1H$  NMR spectra of **L** (Fig. 5), upon the addition of 1.0 equiv. of  $I^-$  to the solution of **L** ( $CDCl_3/CD_3CN$ , v/v, 10:1), the chemical shift of proton  $H_a$  on the amide groups exhibited a significant upfield shift by  $\delta$  0.19 ppm from 9.56 to 9.37 ppm, which confirms the  $C-H \cdots I^-$  interaction between **L** and  $I^-$  ion. The methylene protons  $H_b$  on the  $OCH_2CO$  groups displayed a downfield shift by  $\delta$  0.22 ppm from 4.59 to 4.81 ppm. The bridge

methylene protons  $H_c$  on the  $ArCH_2O$  groups observed as one pair of doublet demonstrated upfield shift from  $\delta$  4.58 to 4.44 ppm (equatorial protons) and 5.21 to 5.12 ppm (axial protons), respectively. In addition, the protons of pyrene moieties underwent upfield or downfield shift respectively, which is mainly attributed to the different shielding effect caused by the conformation change of homooxalix[3]arene skeleton. These data strongly suggested that there must be a conformational change for **L** in the presence of  $I^-$  ion. As a matter of fact, previous reports had already clarified that the conformation of homooxalix[3]arene can be pre-organized for the binding of the guest in solution in a manner [43,44]. Based on the above results, a plausible sensing mechanism is therefore depicted in [Scheme 2](#). The  $I^-$  could be selectively bound by a synergistic action of three amide groups, and then the heavy atom effect increase intersystem crossing to the nonemissive triplet state and thus decrease the population of the singlet excited state, quenching the overall fluorescence intensity [45].

#### 4. Conclusion

In summary, a new fluorescent chemosensor **L** based on a amide-functionalized pyrenyl-appended  $C_{3v}$  symmetric homooxalix[3]arene was synthesized for the selective detection of  $I^-$ . Chemosensor **L** exhibited a high affinity and selectivity for  $I^-$  ion relative to most other competitive anions as evidenced by the dramatic fluorescence quenching. Homooxalix[3]arene with the unique  $C_3$  symmetry is beneficial to the design and synthesis of highly selective chemosensors for anion analyte.

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#### Supplementary data

Electronic Supplementary Information (ESI) available: Details of the fluorescence titration experimental data.

#### References

- [1] Lazarus JH. The importance of iodine in public health. *Environ Geochem Hlth* 2015; 37: 605–18.
- [2] Zimmermann MB. **The role of iodine in human growth and development.** *Semin Cemin Cell Dev* 2011; 22: 645–52.
- [3] Zimmermann MB. Iodine deficiency. *Endocr Rev* 2009; 30: 376–408.
- [4] Azizi F, Hedayati M, Rahmani M, Sheikholeslam R, Allahverdian S, Salarkia N. Reappraisal of the risk of iodine-induced hyperthyroidism: an epidemiological population survey. *J Endocrinol Invest* 2005; 28: 23–9.
- [5] Yebra MC, Cespón RM, Indirect automatic determination of iodide by flame atomic absorption spectrometry. *Anal Chim Acta* 2000; 405: 191–6.
- [6] Phokharatkul D, Karuwan C, Lomas T, Nacapricha D, Wisitsoraat A, Tuantranont

- A. AAO-CNTs electrode on microfluidic flow injection system for rapid iodide sensing. *Talanta* 2011; 84: 1390–5.
- [7] Zhang J, Xu X, Yang C, Yang F, Yang X. Colorimetric iodide recognition and sensing by citrate-stabilized core/shell Cu@Au nanoparticle. *Anal Chem* 2011; 83: 3911–7.
- [8] Thakur A, Bhatta SR, Mondal B, Kakash D, Chawla P. Naphthalene-glycine conjugate: An extremely selective colorimetric chemosensor for iodide ion in aqueous solution. *Sens Actuators B* 2018; 267: 617–26.
- [9] Ito K, Ichihara T, Zhuo H, Kumamoto K, Timerbaev AR, Hirokawa T. Determination of trace iodide in seawater by capillary electrophoresis following transient isotachophoretic preconcentration: comparison with ion chromatography. *Anal Chim Acta* 2003; 497: 67–74.
- [10] Cunha-Silva H, Arcos-Martinez MJ. Cathodic stripping voltammetric determination of iodide using disposable sensors. *Talanta* 2019; 199: 262–9.
- [11] de Souza FC, Vegas CG, da Silva DAI, Ribeiro MS, Cabral MF, de Melo MA, Mattos RMT, Faria RB, D'Elia E. Amperometric and potentiometric determination of iodide using carbon electrodes modified with salophen complex. *J Electroanal Chem* 2016; 783: 49–55.
- [12] Zhang Y, Yu H, Ma Y, Cui G. Imidazolium ionic liquids as mobile phase additives in reversed phase liquid chromatography for the determination of iodide and iodate. *Anal Bioanal Chem* 2018; 410: 7347–55.
- [13] Huang Z, Zhu Z, Subhani Q, Yan W, Guo W, Zhu Y. Simultaneous determination of iodide and iodate in povidone iodine solution by ion chromatography with homemade and exchange capacity controllable columns and column-switching technique. *J Chromatogr A* 2012; 1251: 154–9.
- [14] Minakata K, Yamagishi I, Kanno S, Nozawa H, Suzuki M, Suzuki O. Determination of iodide in urine using electrospray ionization tandem mass spectrometry. *J Chromatogr B* 2010; 878: 1683–6.
- [15] Macours P, Aubry JC, Hauquier B, Boeynaems JM, Goldman S, Moreno-Reyes R. Determination of urinary iodine by inductively coupled plasma mass spectrometry. *J Trace Elem Med Bio* 2008; 22: 162–5.
- [16] Kolanowski JL, Liu F, New EJ. Fluorescent probes for the simultaneous detection of multiple analytes in biology. *Chem Soc Rev* 2018; 47: 195–208.
- [17] Wu D, Chen L, Lee W, Ko G, Yin J, Yoon J. Recent progress in the development of organic dye based near-infrared fluorescence probes for metal ions. *Coord Chem Rev* 2018; 354: 74–97.
- [18] Gale PA, Caltagirone C. Fluorescent and colorimetric sensors for anionic species. *Coord Chem Rev* 2018; 354: 2–27.
- [19] Salomón-Flores MK, Hernández-Juárez CL, Bazany-Rodríguez IJ, Barroso-Flores J, Martínez-Otero D, López-Arteaga R, Valdés-Martínez J, Dorazco-González A. Efficient fluorescent chemosensing of iodide based on a cationic meso-tetraarylporphyrin in pure water. *Sens Actuators B* 2019; 281: 462–70.
- [20] Alizadeh N, Akbarinejad A, Hosseinkhani S, Rabbani F. Synthesis of highly fluorescent water-soluble polypyrrole for cell imaging and iodide ion sensing. *Anal Chim Acta* 2019; 1084: 99–105.
- [21] Zhang B, He Y, Fan Z. Nitrogen-doped graphene quantum dots as highly sensitive and selective fluorescence sensor detection of iodide ions in milk powder. *J*



Photoch Photobio A 2018; 367: 452–7.

[22] Hou W, Chen Y, Lu Q, Liu M, Zhang Y, Yao S. Silver ions enhanced AuNCs fluorescence as a turn-off nanoprobe for ultrasensitive detection of iodide. *Talanta* 2018; 180: 144–9.

[23] Zor E, Alpaydin S, Arici A, Saglam ME, Bingol H. Photoluminescent nanopaper-based microcuvette for iodide detection in seawater. *Sens Actuators B* 2018; 254: 1216–24.

[24] Teixeira FA, Marcos PM, Ascenso JR, Brancatelli G, Hickey N, Geremia S. Selective binding of spherical and linear anions by tetraphenyl(thio)urea-based dihomooxalix[4]arene receptors. *J Org Chem* 2017; 82: 11383–90.

[25] Marcos PM. Functionalization and properties of homooxalixarenes. In: Neri P, Sessler JL, Wang M-X, editors. *Calixarenes and beyond*, Switzerland: Springer International Publishing; 2016, p. 445–66.

[26] Cottet K, Marcos PM, Cragg PJ. Fifty years of oxalix[3] arenes: a review. *Beilstein J Org Chem* 2012; 8: 201–26.

[27] Wu C, Wang C-Z, Zhu Q, Zeng X, Redshaw C, Yamato T. Click synthesis of a quinoline-functionalized hexahomotrioxalix[3]arene: A turn-on fluorescence chemosensor for Fe<sup>3+</sup>. *Sens Actuators B* 2018; 254: 52–8.

[28] Marcos PM, Teixeira FA, Segurado MAP, Ascenso JR, Bernardino RJ, Cragg PJ, Michel S, Hubscher-Bruder V, Arnaud-Neu F. Complexation and DFT studies of lower rim hexahomotrioxalix[3]arene derivatives bearing pyridyl groups with transition and heavy metal cations. Cone versus partial cone conformation. *J Phys Org Chem* 2013; 26: 295–305.

[29] Talotta C, Gaeta C, De Rosa M, Ascenso J R, Marcos PM, Neri P. Alkylammonium guest induced – fit recognition by a flexible dihomooxalix [4] arene derivative. *Eur J Org Chem* 2016; 158–67.

[30] Gaeta C, Talotta C, Farina F, Teixeira FA, Marcos PM, Ascenso JR, Neri P. Alkylammonium cation complexation into the narrow cavity of dihomooxalix[4] arene macrocycle. *J Org Chem* 2012; 77: 10285–93.

[31] Augusto AS, Miranda AS.; Ascenso JR.; Miranda MQ, Félix V, Brancatelli G, Hickey N, Geremia S, Marcos PM. Anion recognition by partial cone dihomooxalix[4]arene-based receptors bearing urea groups: Remarkable affinity for benzoate ion. *Eur J Org Chem* 2018; 5657–67.

[32] Marcos PM, Teixeira FA.; Segurado MAP, Ascenso JR, Bernardino RJ, Michel S, Hubscher-Bruder V. Bidentate urea derivatives of p-tert-butyl dihomooxalix[4]arene: Neutral receptors for anion complexation. *J Org Chem* 2014; 79: 742–51.

[33] Palmeira T, Miranda AS, Marcos PM, Berberan-Santos MN. Calixarenes as high temperature matrices for thermally activated delayed fluorescence: C<sub>70</sub> in dihomooxalix[4]arene. *Molecules* 2018; 23: 558.

[34] Ikeda A, Hatano T, Shinkai S, Akiyama T, Yamada S. Efficient photocurrent generation in novel self-assembled multilayers comprised of [60]fullerene-cationic homooxalix[3]arene inclusion complex and anionic porphyrin polymer. *J Am Chem Soc* 2001; 123: 4855–6.

[35] Singh M, Singh N, Ascenso JR, Marcos PM. A dihomooxalix[4]arene-gold nanohybrid based colorimetric sensor for sensitive and selective detection of iodide. *Supramol Chem* 2019; 31: 313–21.

- [36] Matsumoto H, Nishio S, Takeshita M, Shinkai S. Syntheses and ion selectivities of tri-amide derivatives of hexahomotrioxacalix[3]arene. Remarkably large metal template effect on the ratio of cone vs. Partial-cone conformers. *Tetrahedron* 1995; 51: 4647–54.
- [37] Yamato T, Zhang F, Tsuzuki H. Synthesis and inclusion properties of  $C_3$ -symmetrically capped hexahomotrioxacalix[3]arenes with ester groups on the lower rim. *Eur J Org Chem* 2001: 1069–75.
- [38] Sahoo SK, Kim G-D, Choi H-J. Optical sensing of anions using  $C_{3v}$ -symmetric tripodal receptors. *J Photoch Photobio C* 2016; 27: 30–53.
- [39] Bondy CR, Loeb SJ. Amide based receptors for anions. *Coord Chem Rev* 2003; 240: 77–99.
- [40] Liao Y-C, Venkatesan P, Wei L-F, Wu S-P, A coumarin-based fluorescent probe for thiols and its application in cell imaging, *Sens Actuators B* 2016; 232: 732–7.
- [41] Lin J-R, Chu C-J, Venkatesan P, Wu S-P, Zinc(II) and pyrophosphate selective fluorescence probe and its application to living cell imaging, *Sens Actuators B* 2015; 207: 563–70.
- [42] Mitra A, Pariyar A, Bose S, Bandyopadhyay P. First phenalenone based receptor for selective iodide ion sensing. *Sens Actuators B* 2015; 210: 712–8.
- [43] Ikeda A, Suzuki Y, Yoshimura M, Shinkai S. On the prerequisites for the formation of solution complexes from [60]fullerene and calix[n]arenes: A novel allosteric effect between [60]fullerene and metal cations in calix[n]aryl ester complexes. *Tetrahedron* 1998; 54: 2497–508.
- [44] Takeshita M, Inokuchi F, Shinkai S.  $C_3$ -symmetrically-capped homotrioxacalix[3]arene. A preorganized host molecule for inclusion of primary ammonium ions. *Tetrahedron Lett* 1995; 36: 3341–4.
- [45] Zhang G, Lu J, Fraser CL. Mechanochromic luminescence quenching: force-enhanced singlet-to-triplet intersystem crossing for iodide-substituted difluoroboron-dibenzoylmethane- dodecane in the solid state. *Inorg Chem* 2010; 49: 10747–9.