

# Detection of $\text{HSO}_4^-$ Ion Based on the Hydrolysis of Diketopyrrolopyrrole-derived Schiff Base with Chromogenic and Fluorogenic Dual Signals

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**Abstract** A new diketopyrrolopyrrole-based Schiff base **L** was synthesized and its anion sensing behavior was explored. **L** showed exclusive response toward  $\text{HSO}_4^-$  ion and also distinguished  $\text{HSO}_4^-$  from other anions by color changes (from dark red to orange) and 21 fold fluorescence enhancement at 370 nm in aqueous solution (THF/ $\text{H}_2\text{O}$ =8/1, v/v). The sensing mechanism was suggested to proceed via a hydrolysis process. The results provided colorimetric and fluorimetric assays to selectively detect the presence of a  $\text{HSO}_4^-$  over a wide range of other interfering anions. The results could potentially be used as a dual colorimetric-fluorescent probe for monitoring  $\text{HSO}_4^-$  levels in physiological and environmental systems.

**Keywords**  $\text{HSO}_4^-$  · Schiff base · Colorimetric · Fluorescent · Hydrolysis

## Introduction

The recognition of biologically important anions has received great attention, owing to their fundamental roles in biology, pharmacology and environmental sciences [1–4]. Among various important anions, hydrogensulfate anion ( $\text{HSO}_4^-$ ) is of particular interest owing to its established role in biological and industrial areas and can be found in agricultural fertilizer, industrial raw materials as pollutants due to their deleterious effect. For example,  $\text{HSO}_4^-$  anion is present in nuclear fuel

waste along with other oxoanions, which eventually get into the environment. Moreover, amphiphilic  $\text{HSO}_4^-$  anion eventually dissociates at high pH to generate toxic sulfate ion ( $\text{SO}_4^{2-}$ ), causing irritation of the skin and eyes and even respiratory paralysis. For these reasons, an improved method for the detection and sensing of  $\text{HSO}_4^-$  ions with high selectivity is of current interest.

On the other hand, in biological and environmental systems, anion-receptor interactions commonly occur in aqueous media. Therefore, much attention has been paid to develop anion sensors that work in the aqueous phase. Given that  $\text{HSO}_4^-$  anion has a large standard Gibbs energy of hydration ( $-1,080 \text{ kJ mol}^{-1}$ ), the recognition and separation of the  $\text{HSO}_4^-$  anion from an aqueous media is a challenging task.

To date, many of the reported  $\text{HSO}_4^-$  anion receptors have relied on hydrogen-bonding motifs and, as a consequence, have displayed poor selectivity in aqueous media [5–19]. To overcome this limitation, reaction-based  $\text{HSO}_4^-$  indicators form the irreversible formation of chemical bonds that can provide chemodosimetric information and develop ratiometric fluorescent probes. Because of their excellent selectivity and sensitivity, Schiff bases based chemodosimeters have proven attractive in this regard [1]. The mechanisms of hydrolysis of Schiff bases by acids and amines have been investigated in great detail [2]. It is well known that the pKa value of  $\text{HSO}_4^-$  is 1.99 (in aqueous medium) and it behaves as a hydrogen ( $\text{H}^+$ ) donor in aqueous/semi-aqueous medium instead of accepting  $\text{H}^+$  as for basic anions such as  $\text{F}^-$  and  $\text{CH}_3\text{COO}^-$ . A few Schiff base-based probes due to  $\text{HSO}_4^-$ -promoted hydrolysis have been developed for detection of  $\text{HSO}_4^-$  [20–22]. In 2012, Virendra et al. clearly demonstrated for the first time that the acidic nature of  $\text{HSO}_4^-$  gave rise to hydrolysis of the Schiff base, which led to the optical changes observed in this family of receptors [21]. Recently, Lin et al. reported selective colorimetric and fluorescent chemodosimeter for  $\text{HSO}_4^-$  based on hydrolysis of Schiff

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base [22]. However, these two chemodosimeters available are restricted to the detection of tetrabutylammonium hydrogensulfate, although water-soluble potassium hydrogen sulfate ( $\text{KHSO}_4$ ) is more widespread in biological and industrial areas. Thus, realization of colorimetric and fluorescent measurements for  $\text{KHSO}_4$  is still a challenge. In addition, the selectivity for only  $\text{HSO}_4^-$  has been a problem; especially, for the two tetrahedral oxyanions,  $\text{HSO}_4^-$  and  $\text{H}_2\text{PO}_4^-$ , which are too much alike [23].

Diketopyrrolopyrrole (DPP) dyes have been chosen as fluorophore signaling units because of their widely accepted superiority e.g., high fluorescence quantum yields, high molar absorptivity, high photostability, visible wavelength absorption and modular nature enabling facile functionalization, etc.. These favorable features have made it possible for DPP dyes to be widely used as fluorophore cores for the construction of fluorescent sensors/labels [24–29], polymer solar cells, field effect transistor and dye sensitizing solar cell [30, 31]. However, to the best of our knowledge, there are no reports on colorimetric and fluorescent probe to detect the presence of a target anion based on a DPP Schiff base platform using hydrolysis mechanism. Here, we have developed a new DPP Schiff base based probe **L**, which enables naked eye and dual channel (absorption and fluorescence) detection of  $\text{HSO}_4^-$ .

## Experimental

### Chemicals and Instruments

All reactants were commercially available and used without further purification.  $\text{KHSO}_4$ , NaF, NaCl, KBr, KI,  $\text{Na}_2\text{CO}_3$ ,

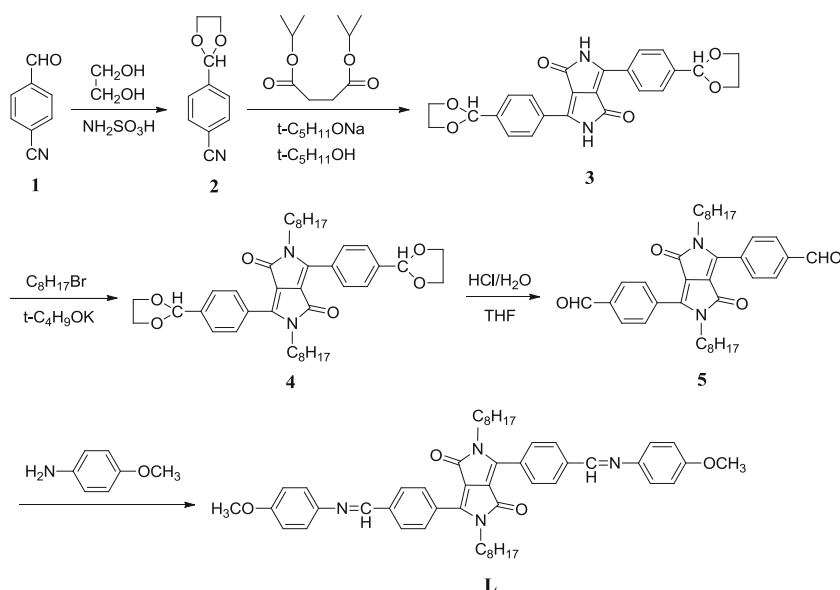
$\text{NaHCO}_3$ ,  $\text{NaHSO}_3$ ,  $\text{Na}_3\text{PO}_4$ ,  $\text{Na}_2\text{HPO}_4$ ,  $\text{NaH}_2\text{PO}_4$ ,  $\text{Na}_2\text{S}$ ,  $\text{NaHS}$ ,  $\text{CH}_3\text{COONa}$ ,  $\text{KCN}$ ,  $\text{KNO}_3$ ,  $\text{KSCN}$  and  $\text{Na}_2\text{SO}_4$  were purchased from Guangzhou Chemical Reagent Company. Compound **5** was prepared according to previous method [32]. Nuclear magnetic resonance was recorded on Bruker Avance III 400 MHz and chemical shifts were expressed in ppm using TMS as an internal standard. The UV–vis absorption spectra were recorded using a Helios Alpha UV–vis scanning spectrophotometer. Fluorescence spectra were obtained with a Hitachi F-4500 FL spectrophotometer with quartz cuvette (path length = 1 cm).

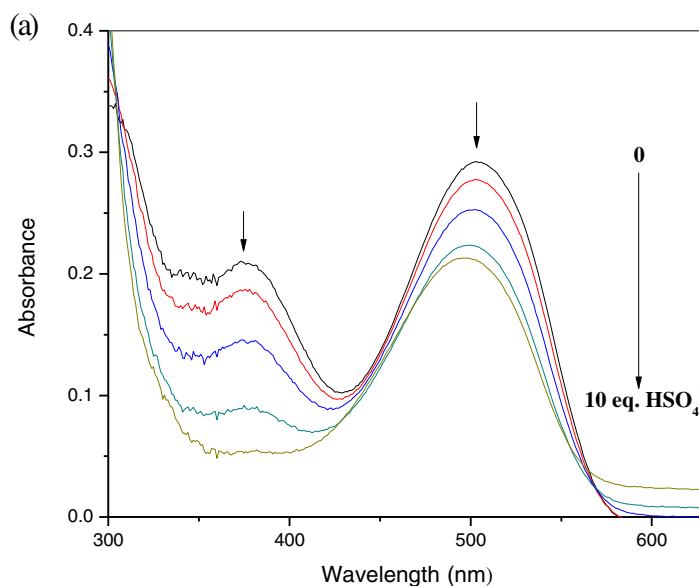
The recognition between DPP-derived Schiff base compound **L** and different anions was investigated by UV–vis and fluorescent spectroscopy in aqueous solution ( $\text{THF}/\text{H}_2\text{O}=8/1$ , v/v) at room temperature. The stock solutions of **L** and anions were at a concentration of 10.0 mM.

### Synthesis of DPP-Derived Schiff Base **L**

A portion of **5** (0.284 g, 0.5 mmol), *p*-methoxyaniline (compound **6**, 0.493 g, 4 mmol) were combined in hot absolute ethanol (20 mL). The solution was stirred under reflux for 6 h to yield a dark red precipitate. The precipitate was filtrated, washed with hot absolute ethanol three times, then recrystallized with ethanol to yield scarlet compound **L** (0.313 g, 0.040 mmol) in 80.5 % yield. m.p. 190–191 °C.  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz,  $\delta$ , ppm): 8.54 (s, 2H,  $-\text{CH}=\text{N}$ ), 8.04–7.92 (m, 8H, ph-H), 7.28 (d, 2H, ph-H), 7.26 (d, 2H, ph-H), 6.96 (d, 4H, ph-H), 4.00 (t, 4H, N- $\text{CH}_2$ ), 3.85 (s, 6H,  $-\text{OCH}_3$ ), 1.59–0.85 (m, 30H,  $-\text{CH}_2$ ,  $-\text{CH}_3$ ).  $^{13}\text{C}$ -NMR ( $\text{CDCl}_3$ , 100 MHz,  $\delta$ , ppm):

**Scheme 1** Synthesis of DPP Schiff base **L**





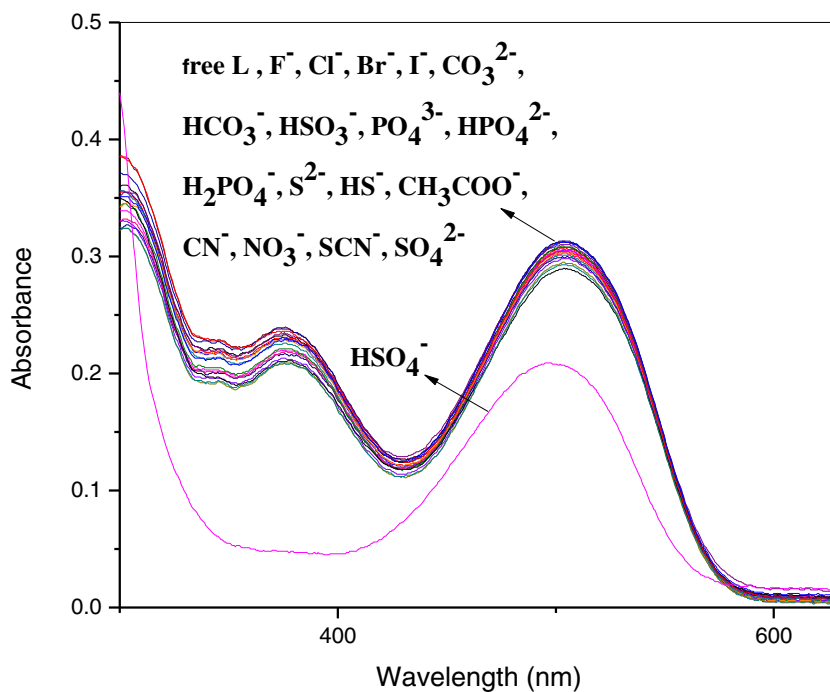
(b)



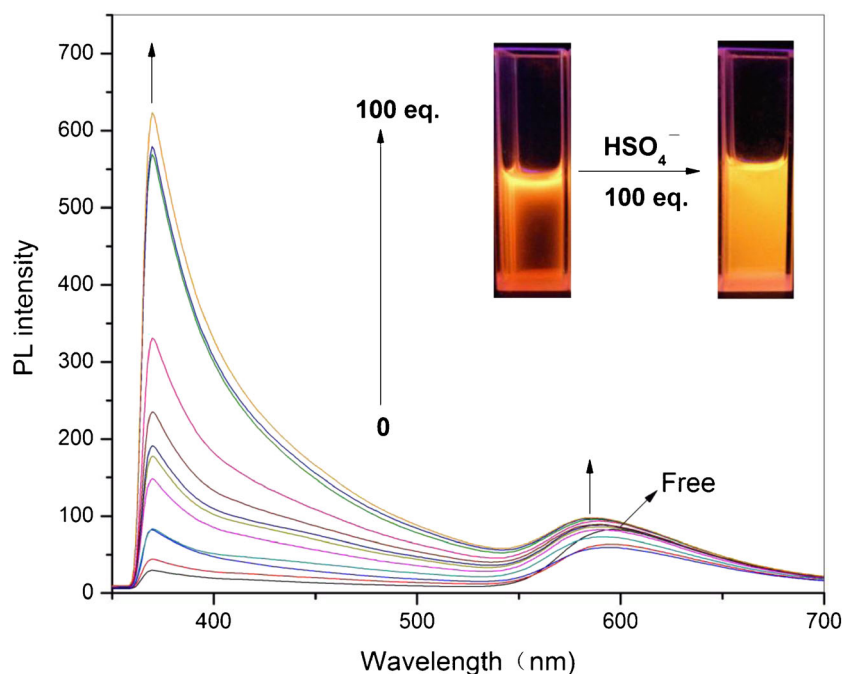
**Fig. 1** a UV–vis absorption spectra of **L** (10.0 μM) with gradual addition of  $\text{HSO}_4^-$  [0, 2, 4, 6, 8 and 10 equiv., respectively] in THF–H<sub>2</sub>O (8/1, v/v); b Color changes of **L** ( $1 \times 10^{-4}$  M) upon addition of different anions in aqueous solution (THF/H<sub>2</sub>O=8/1, v/v)

162.52, 158.71, 156.59, 147.92, 144.25, 138.64, 310.13, 31.73, 29.11, 29.02, 26.73, 22.62, 14.12. ESI-MS m/z: 129.12, 128.76, 122.47, 114.42, 110.36, 55.48, 41.84, 779.4532 [M+H]<sup>+</sup>.

**Fig. 2** UV–vis absorption spectra of **L** (10.0 μM) upon addition of various anion (10 equiv.) in THF–H<sub>2</sub>O (8/1, v/v)



**Fig. 3** Fluorescence spectra of **L** (5.0  $\mu\text{M}$ ) with gradual addition of  $\text{HSO}_4^-$  in THF- $\text{H}_2\text{O}$  (8/1, v/v) with excitation at 366 nm



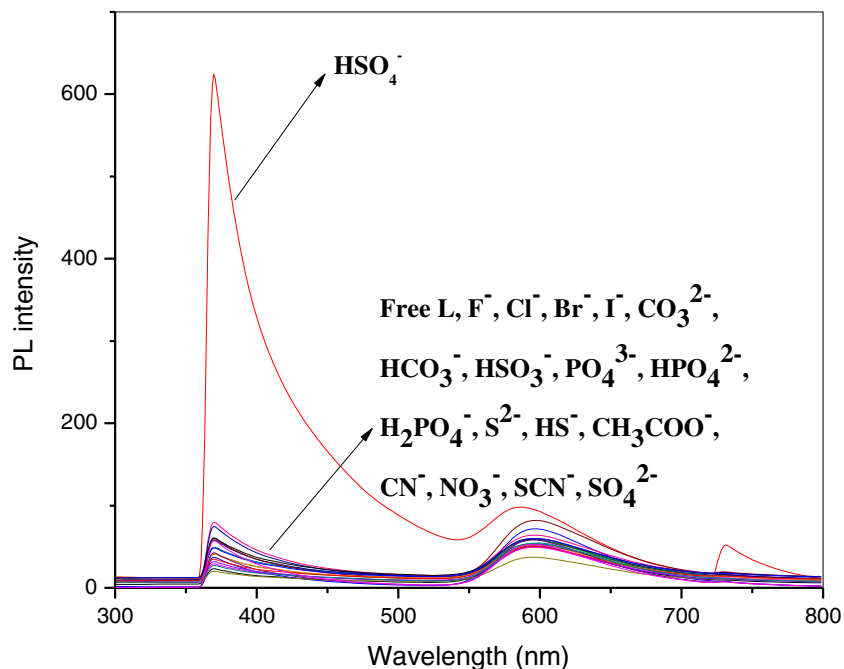
## Results and Discussion

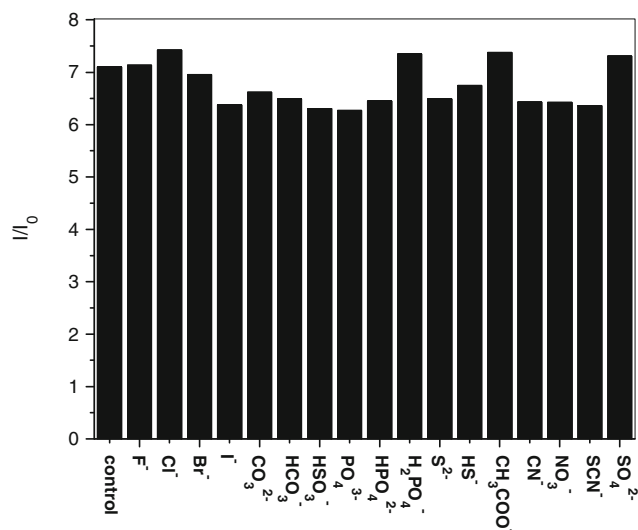
### The Design and Synthesis of Compound **L**

A convenient synthetic route to chemodosimeter **L** was developed as shown in Scheme 1. 2,5-Dioctyl-3,6-bis(4'-formylphenyl)pyrrolo[3,4-c] pyrrole-1,4-dione (compound **5**) was prepared from *p*-cyanobenzaldehyde as a starting

material in four steps. **L** was obtained by condensation of **5** with *p*-methoxyaniline (8 equiv.) in anhydrous ethanol (yield: 80.5 %). The structures of the intermediates and final product were confirmed by NMR spectroscopy (Fig. S1), MS (ESI) analysis (Fig. S2). The  $^1\text{H}$  NMR spectrum of **1** showed one singlet at 3.85 ppm corresponding to methoxyl protons, one triplet at 4.00 ppm corresponding to methylene protons ( $-\text{CH}_2-\text{N}$ ), three doublets at 7.28, 7.26 and 6.96 ppm, one

**Fig. 4** Fluorescent spectra of **L** (5.0  $\mu\text{M}$ ) upon addition of various anion (10 eq) in THF- $\text{H}_2\text{O}$  (8/1, v/v)





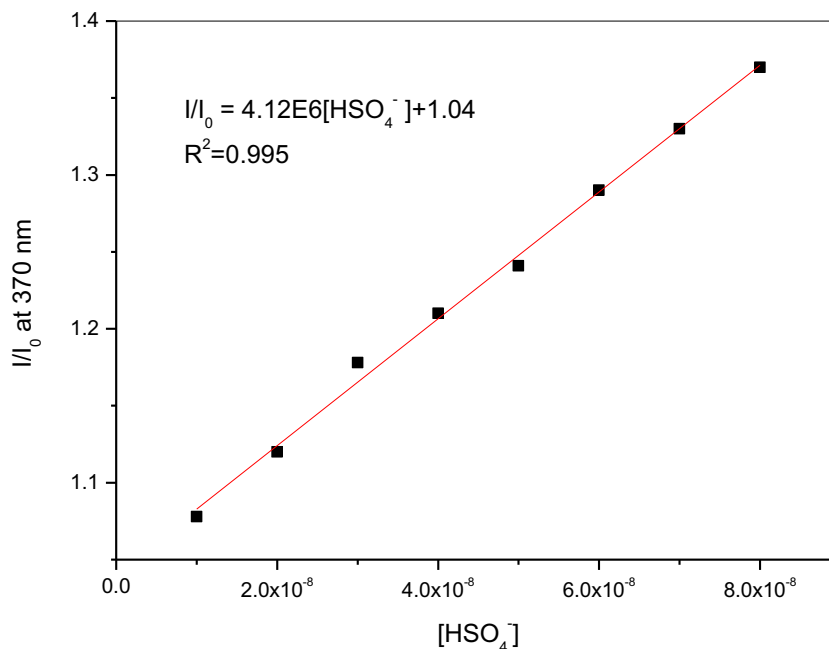
**Fig. 5** Relative fluorescent of **L** (5  $\mu$ M, emission intensity at 366 nm) with 50 equiv. of  $\text{HSO}_4^-$  and 50 equiv. of anion stated

multiplet at 8.04–7.92 ppm corresponding to aromatic protons, and one singlet at 8.54 ppm corresponding to imino protons ( $\text{N}=\text{CH}$ ). The mass spectrum of **1** showed the parent ion peak at  $m/z$  779.4532,  $[\mathbf{1}+\text{H}]^+$ .

#### UV–vis Spectroscopic Studies

The interaction of probe **L** with anions was investigated through spectrophotometric titrations by adding a standard aqueous solution of anions to a 8:1 THF:H<sub>2</sub>O solution of **L**. Free **L** displayed an intense absorption band at 504 nm and a moderate absorption at 366 nm.

**Fig. 6** The linear relation for concentration of  $\text{HSO}_4^-$  in the range of 0–0.8  $\mu$ M.  $I_0$  and  $I$  are the emission intensities at 370 nm of **1** in the absence and presence of  $\text{HSO}_4^-$ , respectively



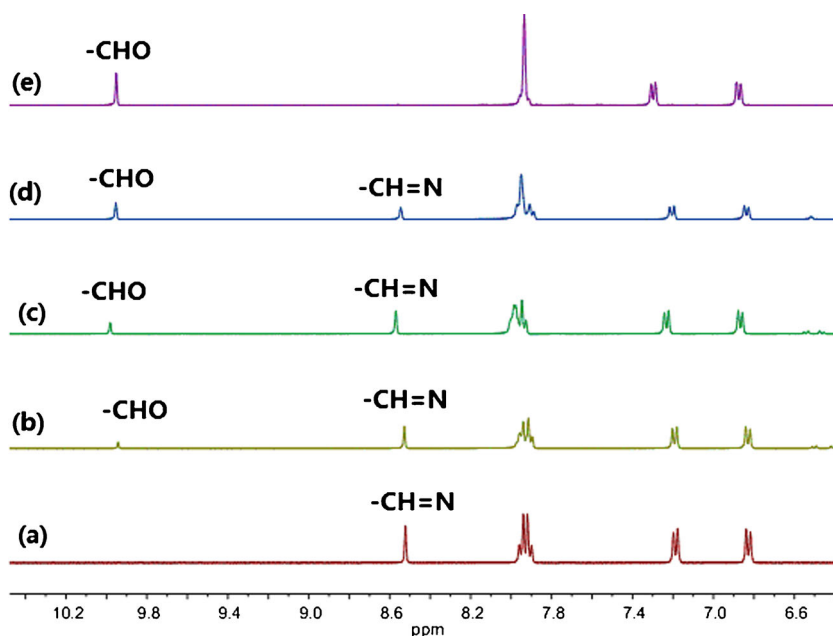
The main band at 504 nm was the typical absorption band of DPP dyes. With gradual addition of  $\text{KHSO}_4$  aqueous solution, the absorption intensity at 366 and 504 nm decreased, as shown in Fig. 1a. Notably, the absorption peak at 366 nm completely disappeared in presence of 10 equiv. of  $\text{HSO}_4^-$ . The dark red color of the probe solution turned orange at the same time, as shown in Fig. 1b. Interestingly, the absorption spectrum of **L** in the presence of 10 equiv.  $\text{HSO}_4^-$  aqueous solution exhibited a similar pattern as that of compound **5** (Fig. S3) and *p*-methoxyaniline (Fig. S4). This led us to speculate if  $\text{HSO}_4^-$  may induce the hydrolysis of **L** to yield compound **5** and *p*-methoxyaniline.

To examine the feasibility of **L** as a  $\text{HSO}_4^-$  probe, analogous investigations were carried out on a variety of anions such as  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{HSO}_3^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{HPO}_4^{2-}$ ,  $\text{H}_2\text{PO}_4^-$ ,  $\text{S}^{2-}$ ,  $\text{HS}^-$ ,  $\text{CH}_3\text{COO}^-$ ,  $\text{CN}^-$ ,  $\text{NO}_3^-$ ,  $\text{SCN}^-$  and  $\text{SO}_4^{2-}$ . As shown in Fig. 2, other anions did not cause significant absorption spectral changes of **L**. However, under the same conditions, only  $\text{HSO}_4^-$  resulted in obvious changes, indicating **L** had stronger UV–Vis absorption response toward  $\text{HSO}_4^-$  than other surveyed metal ions.

#### Fluorescent Spectroscopic Studies

The photophysical properties of **L** in presence of anions were then studied in 8:1 THF:H<sub>2</sub>O solution by emission spectroscopy. The results obtained were in good agreement with those of UV–vis absorption spectroscopy. Upon excitation at 366 nm, free **L** displayed weak

**Fig. 7** Partial  $^1\text{H}$  NMR changes upon the addition **a** 0 equiv.; **b** 0.5 equiv.; **c** 1.0 equiv.; **d** 1.5 equiv.; **e** 2.0 equiv. of  $\text{HSO}_4^-$  in  $\text{THF-}d_8/\text{D}_2\text{O}$  (8:1, v/v)

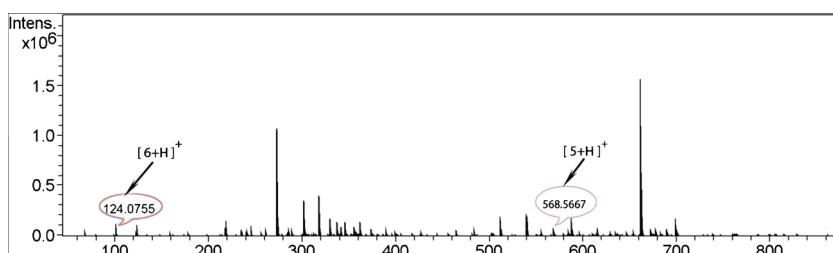


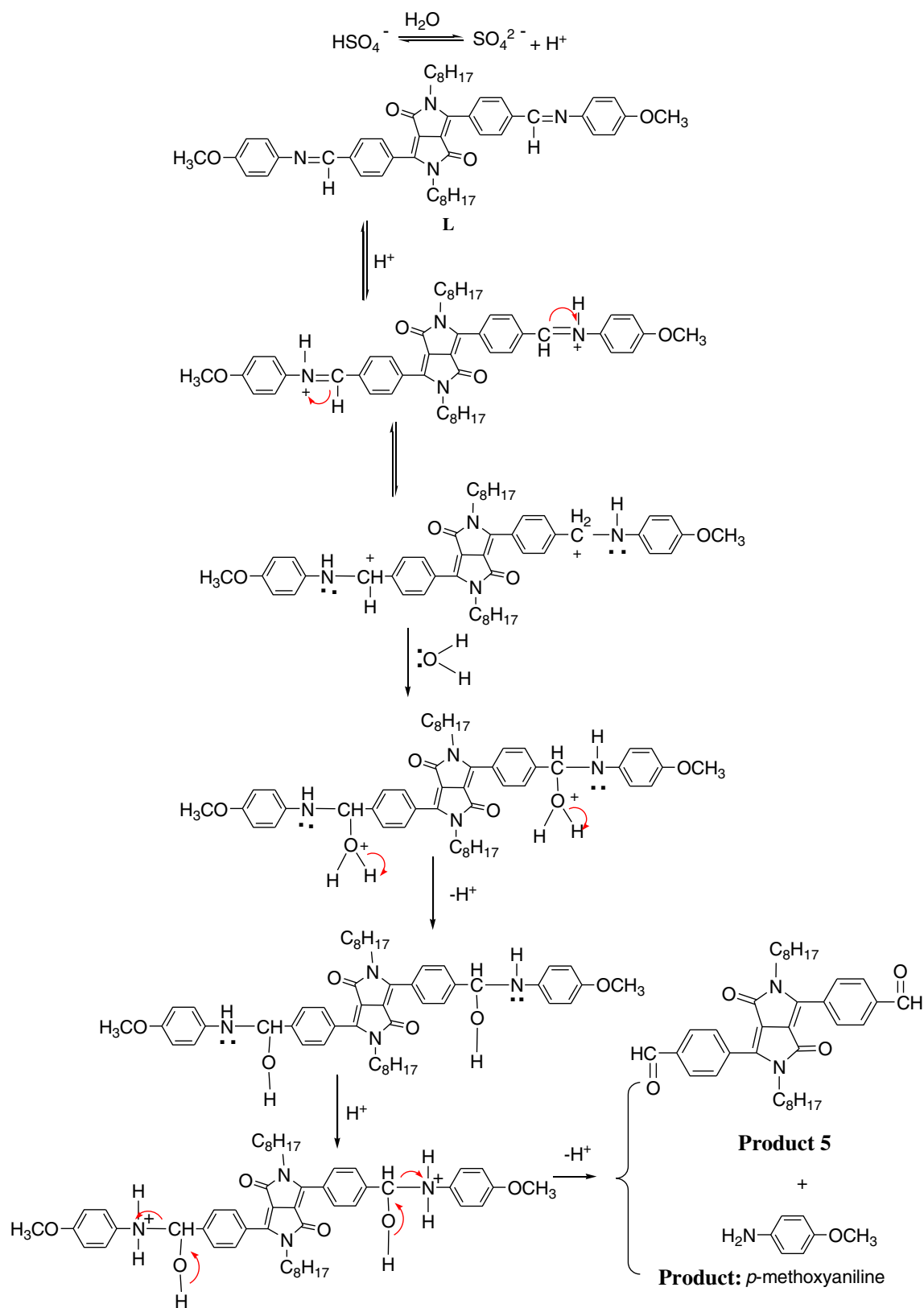
emission bands at 370 and 597 nm, due to a photo-induced charge transfer process (from the electron-donating C=N moiety to the DPP ring), which quenched the excited state emission of the DPP fluorophore. As shown in Fig. 3, upon progressive addition of  $\text{HSO}_4^-$ , the intensity at 370 nm gradually increased, and a small hypsochromical shift (7 nm) of the maximum could be observed at 590 nm. What caught our attention was that the emission spectra of **L** after the addition of  $\text{HSO}_4^-$  were similar to that of compound **5**, since **5** showed emission maxima at 370 nm and 590 nm (Fig. S5). Finally, a plateau with the addition of 500  $\mu\text{M}$  (100 equiv.) of  $\text{HSO}_4^-$  ions was achieved, resulting in 21 fold fluorescence enhancements at 370 nm and slightly increased emission at 590 nm. As the changes in fluorescence intensity are significant, it may be considered that the fluorescence emission is “switched off” in **L** and “switched on” upon the addition of  $\text{HSO}_4^-$ . To gain insight into the whole process, we recorded the absorption and emission spectra of aldehyde **5** and *p*-methoxyaniline in presence of  $\text{HSO}_4^-$  (Figs. S6–S8).

Interestingly, the absorption/emission spectrum of **1** in the presence of  $\text{HSO}_4^-$  ions in mixed aqueous media exhibited a similar pattern as that of the absorption/emission spectrum obtained in the case of aldehyde **5** and amine **6**. From this result, we proposed that **1** was hydrolyzed in the presence of  $\text{HSO}_4^-$  ions aqueous media, generating fluorescent aldehyde **5** and *p*-methoxyaniline.

In order to test whether **L** can be a fluorescent probe for  $\text{HSO}_4^-$ , comparative fluorescence changes upon addition of various anions including  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{HSO}_3^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{HPO}_4^{2-}$ ,  $\text{H}_2\text{PO}_4^-$ ,  $\text{S}^{2-}$ ,  $\text{HS}^-$ ,  $\text{CH}_3\text{COO}^-$ ,  $\text{CN}^-$ ,  $\text{NO}_3^-$ ,  $\text{SCN}^-$  and  $\text{SO}_4^{2-}$  to probe **L** are shown in Fig. 4. These anions gave no distinct response to the solution of **L** in fluorescence spectra, except  $\text{HS}^-$  induced 2.1 fold fluorescence enhancement at 370 nm. However, such a variation in fluorescence intensity by  $\text{HS}^-$  was relatively small compared with that of  $\text{HSO}_4^-$  (21-fold fluorescence enhancement at  $\lambda_{\text{max}}$  370 nm, indicating that **L** showed the stronger response in fluorescence spectrum to  $\text{HSO}_4^-$  among these anions.

**Fig. 8** Mass spectrum of **L** in the presence of  $\text{HSO}_4^-$





**Scheme 2** The possible hydrolysis of **L** in presence of  $\text{HSO}_4^-$  in THF- $\text{H}_2\text{O}$  ( 8/1, v/v)

## Competition Experiment

Competition experiment was carried out to test whether **L** can selectively recognize  $\text{HSO}_4^-$  in the presence of other anions. **L** was treated with 50 equiv. of  $\text{HSO}_4^-$  and 50 equiv. of other surveyed anion. As shown in Fig. 5, miscellaneous competitive anions did not cause significant effect on the sensing of  $\text{HSO}_4^-$ .  $\text{HSO}_4^-$  still exhibited similar fluorescent changes in the presence of various other anions, indicating that there was no interference from other surveyed anions.

The detection limit of **L** for  $\text{HSO}_4^-$  was calculated based on the fluorescence titration data according to a reported method [33]. Under optimal conditions, calibration graphs for the determination of  $\text{HSO}_4^-$  were constructed (Fig. 6). The detection limit for  $\text{HSO}_4^-$  were determined as  $6.45 \times 10^{-9}$  M based on  $S/N=3$ .

## Proposed Mechanism for Interaction of **L** with $\text{HSO}_4^-$

Schiff bases are prone towards hydrolysis in acidic medium as well as through a few metal ions [34–36]. pKa value of  $\text{HSO}_4^-$  is 1.99 (in aqueous medium) and it behaves as a hydrogen ( $\text{H}^+$ ) donor in aqueous/semiaqueous medium [20]. In order to understand the mode of interaction between  $\text{HSO}_4^-$  and **L** in solution and hence to explore the mechanism behind the observed UV–vis absorption and fluorescence response, we carried on  $^1\text{H}$  NMR spectral studies to investigate whether  $\text{HSO}_4^-$  caused the cleavage of **L**. As shown in Fig. 7, free **L** had a singlet at  $\delta$  8.53 ppm assigned to imino protons ( $\text{N}=\text{CH}$ ). After addition of 2 equiv.  $\text{HSO}_4^-$ , the singlet at  $\delta$  8.53 ppm disappeared and a new singlet at  $\delta$  10.06 ppm corresponding to aldehyde protons ( $-\text{CHO}$ ) appeared. The  $^1\text{H}$  NMR spectral studies clearly showed that **L** was hydrolyzed in the presence of  $\text{HSO}_4^-$  in mixed aqueous media to yield compound **5**.

More direct evidence was obtained by comparing the mass spectra of compound **L** and **L**- $\text{HSO}_4^-$ . In Fig. S2, the unique peak at  $m/z=779.4532$  (calcd=779.4531) corresponding to  $[\text{L} + \text{H}]^+$  was observed. While in Fig. 8, with 10 equiv. of  $\text{HSO}_4^-$  added to **L**, the peak at  $m/z=779.4532$  disappeared. Meanwhile, the mass spectral analysis showed peaks corresponding to aldehyde **5** (at  $m/z$  568.5667,  $[\text{5} + \text{H}]^+$ ) and *p*-methoxyaniline **6** (at  $m/z$  124.0755,  $[\text{6} + \text{H}]^+$ ). The MS studies suggested that compound **L** underwent hydrolytic cleavage at the  $\text{C}=\text{N}$  bond in presence of  $\text{HSO}_4^-$ , thus generating aldehyde **5** and *p*-methoxyaniline.

In our case, the distinct color change and large fluorescence enhancement of **L** was due to  $\text{HSO}_4^-$ -promoted hydrolysis. The acid catalyzed mechanism, involves the attachment of a proton on the imino nitrogen followed by the attack of a  $\text{H}_2\text{O}$  molecule on the imine carbon eventually leading to the

cleavage of the imine bond to generate aldehyde and amine, as depicted in Scheme 2.

## Conclusions

In conclusion, we have developed a new DPP Schiff base **L** based colorimetric and fluorimetric probe for  $\text{HSO}_4^-$  anions in aqueous solution ( $\text{THF}/\text{H}_2\text{O}=8/1$ , v/v) with good selectivity. The system provides chromogenic and fluorogenic dual signals by displaying (i) a orange color and (ii) a strong orange fluorescence from an initially dark red and weak orange fluorescent solution, upon exposure to  $\text{HSO}_4^-$ . The drastic color change and strong fluorescence change of **L** are driven by hydrolysis of **L** in presence of  $\text{HSO}_4^-$ . The results could potentially be used as a dual colorimetric-fluorescent probe for monitoring  $\text{HSO}_4^-$  levels in physiological and environmental systems.

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## References

- Shao J, Lin H, Lin HK (2008) *Talanta* 75:1015–1020
- Khanmohammadi H, Rezaeian K (2014) *RSC Adv* 4:1032–1038
- Mahapatra AK, Maji R, Maiti K, Adhikari SS, Mukhopadhyay CD, Mandal D (2014) *Analyst* 139:309–317
- Li Q, Yue Y, Guo Y, Shao SJ (2012) *Sensors Actuators B* 173:797–801
- Alfonso M, Tárraga A, Molina P (2011) *Org Lett* 13:6432–6435
- Chawla HM, Sahu SN, Shrivastava R (2007) *Tetrahedron Lett* 48: 6054–6058
- Zhou LL, Sun H, Li HP, Wang H, Zhang XH, Wu SK, Lee ST (2004) *Org Lett* 6:1071–1074
- Li P, Zhang YM, Lin Q, Li JQ, Wei TB (2012) *Spectrochim Acta Part (A)* 90:152–157
- Xue WJ, Li L, Li Q, Wu AX (2012) *Talanta* 88:734–738
- Tan CL, Wang QM (2011) *Inorg Chem* 50:2953–2956
- Jeon NJ, Ryu BJ, Park KD, Lee YJ, Nam KC (2010) *Chem Soc* 31: 3809–3811
- Kaur P, Kaur H, Singh K (2013) *Analyst* 138:425–428
- Song NR, Moon JH, Choi J, Jun EJ, Kim Y, Kim SJ, Lee JY, Yoon J (2013) *Chem Sci* 4:1765–1771
- Sessler JL, Katayev E, Pantos GD, Ustynyuk YA (2004) *Chem Commun* 40:1276–1277
- Nam KC, Kang SO (1999) *Tetrahedron Lett* 40:7343–7346
- Kang SO, Day VW, James KB (2009) *Org Lett* 11:3654–3657
- Kaur K, Bhardwaj VK, Kaur N, Singh N (2012) *Inorg Chem Commun* 18:79–82



18. Huang G, Zhang G, Zhang D (2012) *Chem Commun* 48:7504–7506
19. Alfonso M, Espinosa A, Tárraga A, Molina P (2012) *Chem Commun* 48:6848–6850
20. Kim HJ, Bhuniya S, Mahajan RK, Puri R, Liu HG, Ko KC, Lee JY, Kim JS (2009) *Chem Commun*:7128–7130
21. Kumar V, Kumar A, Diwan U, Upadhyay KK (2012) *Chem Commun* 48:9540–9542
22. Lin CY, Huang KF, Yen YP (2013) *Spectrochim Acta Part (A)* 115: 552–558
23. Katayev EA, Ustynyuk YA, Sessler JL (2006) *Coord Chem Rev* 250: 3004–3037
24. Deng L, Wu WT, Guo HM, Zhao JZ, Ji SM, Zhang X, Yuan XL, Zhang CL (2011) *J Org Chem* 76:9294–9304
25. Kaur M, Yang DS, Choi K, Cho MJ, Choi DH (2014) *Dyes Pigments* 100:118–126
26. Zhang G, Bi S, Song L, Wang F, Yu J, Wang L (2013) *Dyes Pigments* 99:779–786
27. Qu Y, Hua JL, Tian H (2010) *Org Lett* 12:3320–3323
28. Qu Y, Qu S, Yang L, Hua JL, Qu DH (2012) *Sensors Actuators B* 173: 225–233
29. Ramakrishnam MV, Lin HC (2013) *Org Lett* 15:1274–1277
30. Ftouni H, Bolze F, Rocquigny HD, Nicoud JF (2013) *Bioconjug Chem* 24:942–950
31. Zhou E, Yamakawa S, Tajima K, Yang CH, Hashimoto K (2009) *Chem Mater* 21:4055–4061
32. Jin Y, Xu YB, Liu YL, Wang LY, Jiang HF, Li XJ, Cao DR (2011) *Dyes Pigments* 90:311–318
33. Tong C, Xiang G, Lumin J (2007):575–580
34. Jung HS, Han JH, Kim ZH, Kang C, Kim JS (2011) *Org Lett* 13: 5056–5059
35. Lee MH, Giap TV, Kim SH, Lee YH, Kang C, Kim JS (2010) *Chem Commun* 46:1407–1409
36. Jung HS, Han JH, Habata Y, Kang C, Kim JS (2011) *Chem Commun* 47:5142–5144