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An AIE active monoimidazolium skeleton: high selectivity and fluorescence turn-on for $H_2PO_4^-$ in acetonitrile and ClO_4^- in water⁺

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We disclose herein a monoimidazolium skeleton 1 with an aggregationinduced emission (AIE) characteristic. This fluorogenic skeleton exhibited high selectivity and fluorescence turn-on for $H_2PO_4^-$ in acetonitrile and ClO_4^- in water.

Anions play fundamental roles in life processes and environmental science, so the selective detection of a certain anion is of vital significance and is an important topic in supramolecular chemistry.¹ During the past few decades, fluorescent sensors for non-spherical anions have generally been constituted by multiple binding units in a suitable geometry connected with a fluorescent unit. The design is based on synergistic weak interactions (hydrogen bonding, electrostatic interaction, *etc.*) between the binding units and the anions, and the corresponding fluorescence variation through PET, MLCT and excimer formation mechanisms.² Therefore, the anion recognition in water is highly challenging due to the strong interaction between the anion and water.³

In 2001, Tang *et al.* discovered that molecules with restricted intramolecular rotations were not or weakly fluorescent in dilute solutions, but emitted strong fluorescence upon aggregation, which they referred to as aggregation-induced emission (AIE).⁴ Since then, AIE has attracted much attention as a novel mechanism for the sensor design for metal ions and biological molecules.⁵ However, reports on anions are rare. Zhang's group used the classical AIE active skeletons, a silole⁶ and tetraphenyl-ethylene,⁷ to realize fluorescence turn-on sensing of CN⁻ induced by chemical reactions. A poly(squaramide) synthesized by Taylor *et al.* was reported to aggregate and show fluorescence turn-on triggered by $H_2PO_4^{-.8}$

The imidazolium motif is prevalently used as the binding unit in anion recognition due to its inherent cationic and C-2 hydrogen bond donating characteristics. Massive publications have been reported on bi-, tris- and tetra-imidazolium receptors for various anions according to their sizes and shapes.⁹ However, unidentate imidazolium sensors for nonbasic anions, *i.e.* sensors not based on deprotonation, have not been reported yet.¹⁰ Recently, the imidazolium moiety has exhibited potential as a fluorescent skeleton due to its aromaticity.¹¹ Herein, we present the first AIE active monoimidazolium skeleton **1**, which can act as a highly selective fluorescence turn-on sensor for not only $H_2PO_4^-$ in acetonitrile (MeCN), but also ClO_4^- in water.

Our design is simply based on a typical D– π –A structure, in which the biphenyl group (the π unit) bridges the diphenylamino group (the electron-donating unit, D) and the imidazolium group (the electron-accepting unit, A). This structure is supposed to possess the twisted intramolecular charge transfer (TICT) property¹² and thereby to manifest the AIE effect.⁴

The synthetic route of compound **1** is illustrated in Scheme **1**. The Suzuki–Miyaura coupling of the boronic acid **2** with **1**-(4-bromophenyl)-1*H*-imidazole gave the imidazole precursor **3** in 74% yield. The quaternization of **3** by iodomethane in dry toluene under reflux resulted in the formation of white precipitates, which were filtered off and purified by column chromatography on silica gel to afford pure **1**·I in 72% yield. The structure of **1**·I was characterized by ¹H NMR, ¹³C NMR and HRMS (ESI[†]).



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Fig. 1 Plot of the emission intensity of compound $1 \cdot 1 (10^{-4} \text{ M})$ versus the water fraction in the MeCN–water mixture. Insets: the photos of $1 \cdot 1$ in MeCN (a) and the MeCN/water mixture (b, 1/99, v/v) under UV light and the Tyndall phenomenon.

First, the AIE character of compound 1-I was investigated (Fig. 1). The MeCN solution of $1 \cdot I$ at a concentration of 10^{-4} M was almost not fluorescent until the volume ratio of water increased to 95%. With the continuous addition of water, the fluorescence was steeply intensified and the maximum emission wavelength shifted hypochromically. When the water fraction reached 99%, the solution emitted a deep blue fluorescence under UV irradiation (Fig. 1, inset) and the fluorescence enhanced almost 35-fold with a blue shift of 80 nm (Fig. S1, ESI[†]). Although the solution at this stage was still clear under ambient light, the Tyndall phenomenon disclosed the formation of the nano-sized aggregates of 1-I (Fig. 1, inset).¹³ The lower polarity inside the aggregates was probably responsible for the blue shift of the emission peak.^{4a} In addition, the narrow AIE window indicated the dichotomous solubility of 1.I in MeCN and water.

The anion recognition experiment was then conducted by measuring the fluorescence variation of sensor 1·I in MeCN (10 μ M) upon addition of 10 equiv. of H₂PO₄⁻, ClO₄⁻, HSO₄⁻, AcO⁻, F⁻, Cl⁻ and Br⁻ anions in the form of tetrabutyl-ammonium (TBA) salts (Fig. 2). H₂PO₄⁻ turned on the fluorescence and caused almost 21.3-fold enhancement as measured at 454 nm while other anions induced no or small changes. Notably, the common interfering F⁻ anion only gave 1.4-fold enhancement and the AcO⁻ anion¹⁴ had no effect at all.



Fig. 2 Fluorescence variations of **1**·I (10 μ M) in the presence of different anions (10 equiv.) in MeCN, excited at 351 nm, slit = 3 nm. Insets: (a) the corresponding fluorescence spectra; (b) the photo of **1**·I (10 μ M) with the different anions (10 equiv.) in MeCN under UV light.



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Fig. 3 (a) Fluorescence spectra of **1**·I (10 μ M) in MeCN upon addition of different amounts of TBAH₂PO₄, excited at 351 nm. Inset: the plot of the fluorescence intensity (I_{454}) *versus* the equivalent number of TBAH₂PO₄; (b) the corresponding absorption spectra.

The fluorescence difference was clearly seen by the naked eye under UV light (Fig. 2, inset b), which could be used for the selective $H_2PO_4^-$ detection. The fluorescence titration of 1 ·I in MeCN at 10 μ M using $H_2PO_4^-$ (Fig. 3a) gave almost a linear relationship of the fluorescence of 1 ·I *versus* the added anions within 10 equivalents at 454 nm, and the fluorescence remained unchanged upon more $H_2PO_4^-$ addition.

The UV titration experiment showed that the absorption of 1.I around 340 nm upon addition of H₂PO₄⁻ decreased and the level-off tail above 400 nm increased gradually (Fig. 3b). This could be attributed to the light scattering effect of the formed nanoparticles.¹⁵ The dynamic light scattering (DLS) measurement showed an average particle size of 779 nm (PdI = 0.554, Fig. S6a, ESI⁺) in a 10 µM MeCN solution of 1 · I with 10 equiv. of TBAH₂PO₄. At this concentration, no nanoparticle was formed even upon addition of 100 equiv. of other anions as observed by the Tyndall test. At a concentration of 5 imes 10^{-4} M, 50-time stronger concentration for the H₂PO₄⁻ sensing, the Tyndall test showed the formation of nanoparticles caused by the addition of 10 equiv. of TBAF, TBACl and TBAHSO₄, respectively (Fig. S2, ESI[†]). However, only a small increase of the fluorescence was observed. The different fluorescence enhancements induced by different anions suggested that the substructure of the nanoparticles, which was specifically controlled by the anions, was a critical factor to determine the fluorescence emission in this case.

Job's plot measurement (Fig. S3, ESI[†]) revealed that 1·I and $H_2PO_4^-$ formed a 1:1 complex, indicating that the anion exchange occurred and 1·I was converted to $1 \cdot H_2PO_4$. $1 \cdot H_2PO_4$ was collected as a light green precipitate by the addition of TBAH₂PO₄ into a saturated solution of 1·I in MeCN. $1 \cdot H_2PO_4$ was then well dispersed in MeCN by sonication to form a 10 μ M suspension with visible aggregates, which only emitted weak fluorescence under UV light. Its fluorescence intensity was significantly lower than that of the 10 μ M MeCN solution of 1·I upon addition of 10 equiv. of TBAH₂PO₄ (Fig. S4, ESI[†]). This difference demonstrated again that the nanostructure was strongly emissive in the solid state and soluble in water to form a non-emissive solution of THF in the HEPES solution of $1 \cdot H_2PO_4$ lightened up the cyan fluorescence gradually (Fig. S5, ESI[†]).

In consideration of the great challenge of the anion recognition in aqueous solution, the capability of $1 \cdot H_2PO_4$ was tested in the HEPES solution at a concentration of 25 μ M (Fig. 4). To our delight, upon addition of 15 equiv. of various anions such as ClO_4^- , SO_4^{2-} , AcO^- , NO_3^- , HCO_3^- , F^- , Cl^- , Br^- and I^- , only ClO_4^- turned on the

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Fig. 4 (a) Fluorescence spectra of $1 \cdot H_2PO_4$ (25 μ M) in the presence of the sodium salts of different anions (SO₄²⁻, AcO⁻, NO₃⁻, HCO₃⁻, Cl⁻, Br⁻ and l⁻), KF and LiClO₄·3H₂O (15 equiv.) in 10 mM HEPES buffer (pH = 7.4), excited at 355 nm; (b) the corresponding fluorescence variations of $1 \cdot H_2PO_4$ (25 μ M). Inset: the photo of $1 \cdot H_2PO_4$ (25 μ M) with different anions (10 equiv.) in HEPES buffer under UV light.

fluorescence and gave a 14.4-fold enhancement. Small but unnoticeable variation was induced by SO_4^{2-} and I⁻. The other anions did not cause any change at all. The fluorescence difference could also be easily distinguished by the naked eye under UV light (Fig. 4b, inset). Therefore, $1 \cdot H_2PO_4$ could be used as a highly selective fluorescent sensor for ClO_4^- in aqueous solution. To the best of our knowledge, $1 \cdot H_2PO_4$ is the first fluorescence "turn-on" sensor for ClO_4^- in water.¹⁶ The DLS experiment revealed that the nanoparticles were formed in the presence of ClO_4^- and the average size was around 586 nm (PdI = 0.473, Fig. S6b, ESI⁺).

The sensing ability of $1 \cdot H_2PO_4$ toward ClO_4^- was further tested in living cells. When HeLa cells were incubated with $1 \cdot H_2PO_4$ (25 µM) in PBS buffer for 30 min at 37 °C, only faint luminescence was observed in the cells by using the confocal luminescence microscopy (Fig. 5b). After the cells were subsequently incubated with ClO_4^- (15 equiv.) at 37 °C for another 15 min, a strong blue fluorescence in the cytoplasm was clearly seen (Fig. 5d). The bright-field images (Fig. 5a and c) showed that the cells were alive during the incubation period. These results demonstrated that $1 \cdot H_2PO_4$ could penetrate the cell wall and be used for intracellular ClO_4^- imaging *in vitro*.

In conclusion, the first AIE active monoimidazolium skeleton **1** was synthesized. **1**·I could serve as a highly selective fluorescence turn-on sensor for $H_2PO_4^-$ in MeCN. More notably, **1**· H_2PO_4 represented the first highly selective and fluorescence turn-on sensor for ClO_4^- in water. These two sensing processes were both based on

Fig. 5 (a) Bright-field and (b) fluorescence images of the HeLa cells cultured in the presence of $1 \cdot H_2 PO_4$ (25 μ M) in PBS buffer at 37 °C for 30 min; (c) bright-field and (d) fluorescence images after incubation with LiClO₄·3H₂O (15 equiv.) for another 15 min.

the AIE mechanism, and the substructure of the nanoparticles formed was considered to be very crucial. $1 \cdot H_2 PO_4$ was also proven to be applicable for ClO_4^- imaging in live cells. Our work demonstrated that AIE might be an efficient strategy for the challenging anion recognition in competitive solvents such as water.

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