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Version of Record: https://www.sciencedirect.com/science/article/pii/S0278691521007900
Manuscript_072de317651bd5323edc1ca99bd628b6

Seaweed consumption in France: key data for exposure and risk assessment

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Keywords: seaweeds – food – consumption – enquiry – exposure and risk assessment

Word count : 5687

A novel benzotriazole derivate with Twisted Intramolecular Charge Transfer and Aggregation Induced Emission features for proton determination

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Abstract:

Molecules with Aggregation-Induced Emission (AIE) effects could show strong emission in solid or aggregate form, thus they are suitable for applications in the field of solid luminescent materials. According to former reporting, AIE molecules are always J-aggregates. In this study, a new benzotriazole derivate with electron donor-acceptor structure was synthesized. (E)-4-(2-(1H-benzo[d] [1,2,3] triazol-1-yl) vinyl)-N, N-dimethylaniline (BTADA) has both TICT and AIE effect, even though it is H-aggregate. Furthermore, BTADA could respond to proton in solution and solid form. Due to its multiple binging sites, proton would bind to benzotriazole and dimethylaniline moiety successively when BTADA was exposed to acid, and the

fluorescent color changed from green to yellow then blue as the concentration of proton increased. Such phenomena indicate BTADA has potential usage in proton detection.

Keywords Benzotriazole, H-aggregate, Aggregation-Induced Emission, Proton Response, Twisted Intramolecular Charge Transfer

1. Introduction

Normally, chromophoric organic dyes with planar structure always show strong luminescence properties in dispersed states, but the fluorescence will be dramatically quenched in solid or aggregate states because the energy from excited states can decay back via non-radioactive channels like π-π stacking interactions between molecules [1], known as Aggregation-Caused Quenching (ACQ) [2, 3]. Compared with ACQ molecules, molecules with Aggregation-Induced Emission (AIE) effects could show strong fluorescence emission in solid or aggregate form. This effect was first brought by the group of Tang in 2001 [4], and has gained pile of attention since day one. Small organic molecules with AIE effect have stood out of the line due to the obvious advantages in some application fields. AIE molecules are suitable for applications in the field of solid luminescent materials because the luminescent molecules are required to be in a tightly packed aggregate or solid state [5, 6] rather than in a dispersed state in practical applications. In the field of fluorescence analysis, the

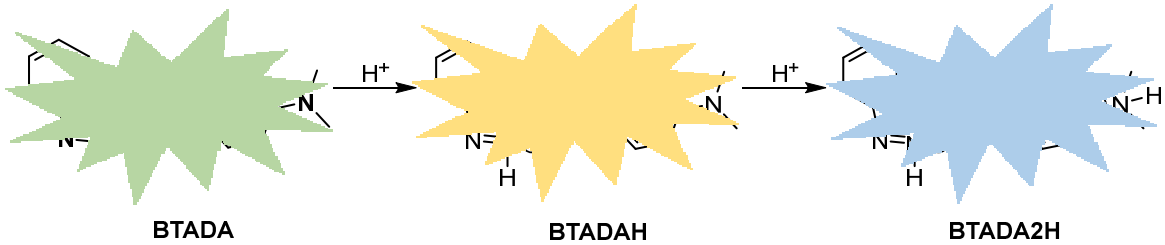
ability of fluorescent probes to detect analytes in high water content systems is sometimes required. Because of hydrophobicity, the organic fluorescent molecules usually form aggregates in water. Traditional organic dyes suffer from ACQ effect and are restricted from application. However, AIE-based probes could be easily engineered and possess high photobleaching resistance. This kind probes can keep high sensitivity and selectivity to detect analytes in aqueous solution. Nowadays, these AIE organic molecules have been widely used in Organic Light-Emitting Diodes (OLEDs) [7 - 9], biosensor (for proteins [10 - 11], DNAs [12 - 14], amino acids [15 - 17], and so on), chemosensor (for ions [18], gases [19], explosives [20 - 21] and so on) and other varies fields.

Many fluorescence molecules have an electron donor-acceptor (D-A) structure. In some cases, there is a bridge that link the electron donor part and the electron acceptor part in fluorescence molecules. When the external conditions change, such as temperature, pressure and polarity of the solvent, these molecules will twist as well. This kind of torsion leads to a charge separation among the whole molecule, narrows the band gap and results in red shift emission. This phenomenon is called “Twisted intramolecular charge transfer” (TICT) [22]. TICT effect of organic compounds have been systematically studied [23 - 25] and always used to detect some target molecules in analytical fields [26 - 28]. In recent years, organic fluorescence molecules with both TICT and AIE effects have attracted extensive attention and been applied in many analytical fields. Some of these TICT-AIE organic molecules like

tetraphenylethene (TPE) derivatives [29], boron dipyrromethene (BODIPY) derivatives [30], cyan derivatives [31 - 33] and 9,10-Bis[4'-(4''-aminostyryl) styryl] anthracene derivatives [34] are J-aggregates when they generate AIE effect. This means they tend to pack in a "head-to-toe" form when these molecules aggregate. J-aggregates of AIE fluorescence molecules share as following characteristics: small Stokes-shift with a narrow band gap and a bathochromic shift of emission wavelength [35]. However, there's another type of aggregation in which the molecules are packed "face-to-face". Apart from J-aggregates, this kind of aggregation with a hypsochromic shift, is normally called "H-aggregate" [36 - 37]. H-aggregates have longer Stokes-shift than J-aggregates. Meanwhile, the UV-vis absorb and fluorescence emission spectra in aggregated states are blue shifted compared with those in dispersed states [35]. But, there are only a few reports about H-aggregate molecules in AIE luminogens. For example, Distyrylbenzene (DSB) [38] is a classic H-type AIE luminogens. Other examples include merocyanine and other dyes containing heteroaromatic rings [39 - 40]. However, it comes to our notice that benzotriazole derivatives as AIE fluorescence molecules are lack study. We hereby reported a new type of benzotriazole derivative that shows AIE effect while aggregating in the H-type.

Benzotriazole, compare to other heteroaromatic compounds, exhibits stronger aromaticity, flatter planarity, and can act like a much stronger electron-acceptor [41]. Naturally, benzotriazole can play an important role among fluorescence organic

molecules. However, correlational research work is rarely reported. In this work, we synthesize (E)-4-(2-(1H-benzo[d] [1,2,3] triazol-1-yl) vinyl)-N, N-dimethylaniline (BTADA). Due to its wide π conjunction and electron donor-acceptor construct, BTADA should exhibit high fluorescence emission in solution system. Following experiments confirmed our conjecture. Moreover, further experiments indicate other unexpected properties. In addition to exhibiting different fluorescence emission wavelength in various solvent, BTADA has strong fluorescence emissive activity in solid form. The single-crystal structure of BTADA clearly shows that BTADA is a classic H-aggregate. As discussed above, AIE property of benzotriazole derivative is rarely seen in H-aggregates. More to that, with the strong electron donor-acceptor structure of BTADA, the benzotriazole part and dimethylamine part are both rotors that can spin over the covalent bond on both sides of alkene bridge. Which makes it a classic TICT molecule. To summarize, during the aggregation of monomer, the BTADA shows TICT-AIE effect. Even more to the point, BTADA exhibited a dual-step response to proton, which means it has a potential application in proton detection.



Scheme 1. Schematic diagram of proton response of BTADA

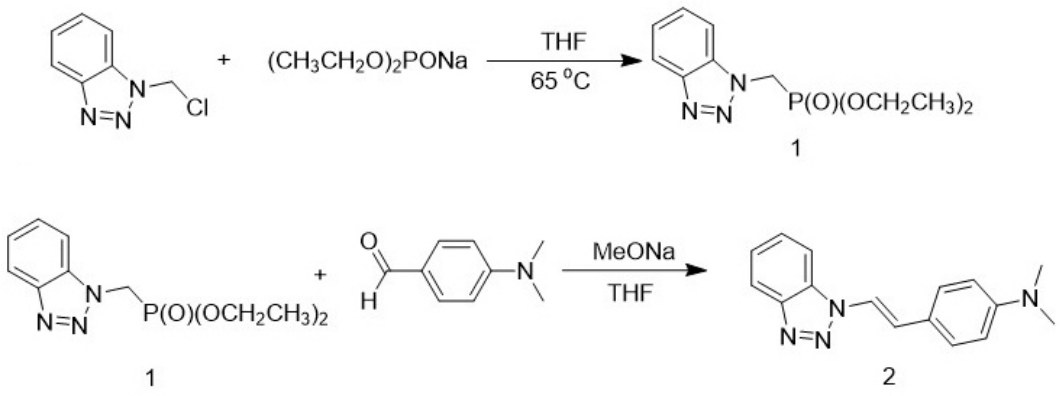
2. Experimental section

2.1. Materials and measurements

All the raw materials were obtained from commercial supplies and used without further purification. THF were dehydrated by reflux with solid Na. Water used throughout all experiments was purified with Millipore system. ^{1}H NMR and ^{13}C NMR spectra were recorded on Bruker 400 NMR spectrometer. Chemical shifts are reported in ppm with TMS as reference. Mass spectra were obtained with Agilent1290 - Bruker microTOF QII mass spectrometer. The UV-vis absorption spectra were obtained using a Shimadzu UV-3100 Spectrophotometer. Fluorescence data was measured on a Hitachi F-2700 Fluor spectrophotometer.

The single crystal of BTADA was obtained from saturated dichloromethane solution by slow evaporation at room temperature. The crystallographic data for BTADA was collected on a Siemens Smart CCD diffractometer with graphite-monochromated Mo-Kα (λ = 0.71073 Å) radiation at room temperature. The structure was solved by direct methods with SHELXT1 and refined by full-matrix least-squares on F^2 using the SHELXTL-20142. All non-hydrogen atoms were refined with anisotropic displacement parameters. The hydrogen atoms of the ligands were generated geometrically.

2.2. Synthesis of BTADA



Scheme 2. Synthesis route of BTADA

2.2.1. Synthesis of Diethyl ((1H-benzo[d] [1,2,3] triazol-1-yl) methyl) phosphonate (1)

Diethyl ((1H-benzo[d] [1,2,3] triazol-1-yl) methyl) phosphonate (**1**) was synthesized according to literature [42].

2.2.2. Synthesis of BTADA

MeONa (1.08 g, 20 mmol) and **1** (5.38 g, 20 mmol) was added to dry THF (20 ml) under N_2, stirred at 0 ℃ for 30 minutes. After which the mixture of 4-Dimethylaminobenzaldehyde (1.49 g, 10 mmol) and THF (5ml) was slowly added to the reaction solution with syringe. The reaction temperature was then heated to reflux. After stirred for 12h under the protection of N_2, the reaction was quenched by water. The aqueous solution was extracted with dichloromethane (3*20ml) and the combined organic phase was dried by Na_2SO_4. The solvent was removed by vacuum evaporation. The crude product was purified by a silica gel column with ethyl acetate and petroleum ether (1:5) as eluent, the products was obtained as yellow crystal in a

yield of 90 % (2.38 g). ^{1}H NMR (400 MHz, Chloroform-*d*): δ 8.10 (d, *J* = 8.3 Hz, 1H), 7.82 – 7.71 (m, 2H), 7.56 (ddd, *J* = 8.1, 6.9, 1.0 Hz, 1H), 7.48 – 7.35 (m, 4H), 6.79 – 6.72 (m, 2H), 3.02 (s, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*): δ 150.62, 146.26, 131.52, 127.86, 127.77, 124.38, 122.34, 122.07, 120.31, 118.14, 112.42, 110.23, 40.38. HRMS: *m/z* 265.1390 [$(M+H)^+$, calcd 265.1409].

2.3 fluorescence experiment

The concentration of BTADA was 1×10^{-5} mol L^{-1}, excitation wavelength was 365 nm, excitation and emission slit were both 5 nm.

2.3.1 fluorescence response to different solvent

BTADA was respectively dissolved in CH_2Cl_2, $CHCl_3$, DMF, THF, Acetone, CH_3CN, ethanol, ethyl acetate, toluene and cyclohexene. The final concentration of BTADA was 1×10^{-5} mol L^{-1}.

2.3.2 fluorescence response to the water fraction of the solvent

BTADA was dissolved in methanol, the concentration of BTADA was 2×10^{-4} mol L^{-1}. Then 100 μL of BTADA solution was diluted with the mixture of methanol and water to 2 mL.

2.3.3 fluorescence response to the viscosity of the solvent

BTADA was dissolved in methanol, the concentration of BTADA was 2×10^{-4} mol L^{-1}. Then 100 μL of BTADA solution was diluted with the mixture of methanol and glycerol to 2 mL.

2.3.4 fluorescence response to proton

BTADA was dissolved in $CHCl_3$, the concentration of BTADA was 2×10^{-4} mol L^{-1}. After different volume of trifluoroacetic acid (TFA, 2.5×10^{-3} mol L^{-1}) was added into BTADA solution, the mixed solution was diluted with $CHCl_3$ to 2 mL.

3. Results and discussion

3.1 Twisted intramolecular charge transfer

BTADA was synthesized through the above reaction procedures as yellow platy crystal. The total yield was 81%. As shown in Fig. 1a, BTADA contains a classic electron donor-acceptor structure. The N, N-dimethylamine part (electron donor) and the benzotriazole part (electron acceptor) in BTADA are connected through a conjugated π-bridge. The existence of rotatable C-C and C-N δ bond on both sides of alkene bridge make them rotors. Meanwhile, the density functional theory (DFT) was used to calculate the charge distribution in BTADA. The results are shown in Fig. S3. In the highest occupied molecular orbital (HOMO) of BTADA, most of the electron density is on the N, N-dimethylamine part (electron donor), while in the lowest unoccupied molecular orbital (LUMO) of BTADA, most of the electron density is on the benzotriazole part (electron acceptor).

Generally, fluorophores comprise D-π-A conjugated structures that usually form TICT states upon light irradiation. BTADA as a D-π-A structure molecule has two kinds of excited states, locally excited (LE) state and TICT state (Fig. 1b). Through the effect of external conditions, LE state and TICT state can be easily transformed into each other. When dissolved in low-polar solvent, BTADA is in a coplanar

conformation and the LE state is the lowest-energy state. As shown in Fig. 1c, the cyclohexane solution of BTADA was observed a strong fluorescence emission wavelength at 449 nm when the excited wavelength is 365 nm. With the increase of the polarity of the solvent, the multiple interactions between the electron donor and acceptor parts of BTADA can enhance the HOMO level and reduce the LOMO level resulting in a TICT state. Meanwhile, the fluorescence emission of BTADA has an obvious bathochromic-shift as the polarity of solution increases and BTADA displayed different fluorescene colors from blue to orange in different polarity solvents. (Fig. 1c and 1e). As shown in Fig. 1d, the polar function (Δ f) of solvents and the Stokes shift (Δ v) shows ideal linear relationships and fitted well with the Lippert–Mataga plot [43]. These experimental results confirm the TICT property of BTADA by the solvent polarity dependent fluorescent emission [44].

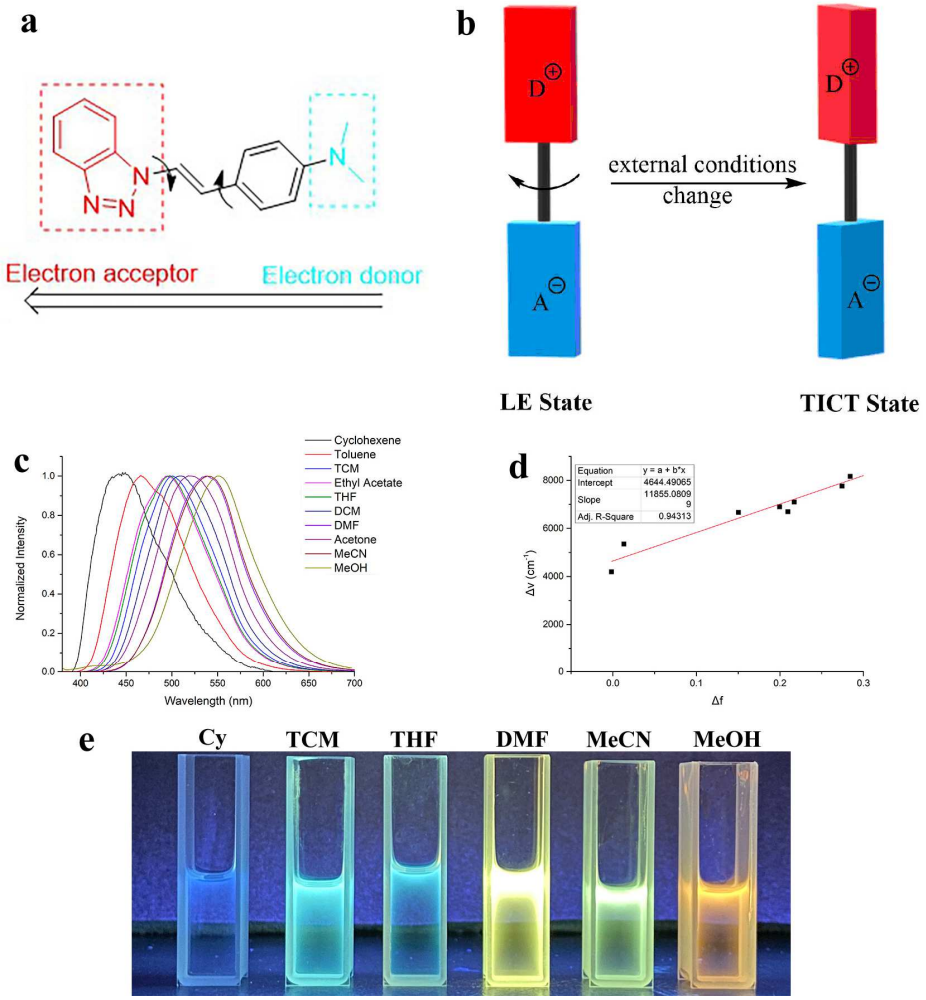


Fig. 1. (a). Electron structure of BTADA; (b). LE state and TICT state of BTADA; (c). Fluorescence photographs of BTADA in different solvent; (d). Plot of the Stokes shift of BTADA in each solvent versus Δf of the respective solvent. The concentrations of BTADA in the experiments are 50 μM; (e). Fluorescence images of BTADA in different solvent

3.2 Aggregation-induced emission effect of BTADA

In this part, the fluorescence emission behaviors of BTADA in H_2O-MeOH solution with different water contents (f_w, the volume percentage of water in H_2O-MeOH solution) were studied. As shown in Fig. 2a and 2b, the yellow fluorescence (550 nm) can be observed under 365 nm as excitation wavelength when BTADA is dissolved in

pure ethanol. The fluorescence of BTADA is slightly bathochromic-shift and gradually weakens When water contents are increased from 0 to 70 % in H_2O-MeOH solution, which is a sign that the BTADA molecule has turned into a TICT state. While the f_w is over 70%, the fluorescence emission intensity is dramatically increased and fluorescence emission wavelength has obviously blue-shifted into 507 nm under 365 nm as excitation wavelength. In this stage, BTADA molecules are easy to aggregate due to the hydrophobic interaction. Such aggregation will lead to the restriction of intramolecular rotations (RIR), thus the non-radioactive channel for excited state to decay back to ground state are cut off, resulting in Aggregation-Induced Emission [45]. To further explain the mechanism of the BTADA molecules' AIE effect, photophysical behaviors of BTADA were studied in the system of methanol-glycerol mixture as well (Fig. 2c). When the volume percentage of glycerol in glycerol-MeOH solution (f_g) is increased, the viscosity of methanol-glycerol mixture solution goes up, and so does the fluorescence intensity of BTADA. It indicates that BTADA is harder and harder to rotate when the viscosity of solution is gradually increased. This also proves the RIR is the reason for the AIE effect of BTADA.