ORGANIC CHEMISTRY FRONTIERS

RESEARCH ARTICLE

View Article Online
View Journal | View Issue

Cite this: *Org. Chem. Front.*, 2023, **10**, 2913

Ratiometric sensing of β-galactosidase based on excited-state intramolecular proton transfer (ESIPT) and solid-state luminescence enhancement†

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Received 23rd April 2023,
Accepted 9th May 2023

DOI: 10.1039/d3qo00605k

rsc.li/frontiers-organic

Glycosidases play important roles in modulating the structural and functional integrity of glycoproteins and glycolipids, and thus are promising biomarkers for disease diagnosis. While current approaches for glycosidase detection mainly rely on an enhancement of the UV-vis absorbance or fluorescence emission of glycosyl indicators, here we develop a ratiometric fluorescent probe for the sensitive and selective detection of glycosidase activity based on the combined mechanisms of excited-state intramolecular proton transfer (ESIPT) and solid-state luminescence enhancement (SSLE). The probe behaves like a typical SSLE when glycosylated, and exhibits a ~140 nm red-shift in fluorescence owing to activation of ESIPT after deglycosylation. Such a large Stokes shift may facilitate the unbiased analysis of glycosidase activities when used in diagnostic and drug-screening assays.

Glycosylation and deglycosylation reactions of biomacromolecules including proteins, peptides and lipids are implicated in a myriad of biological and pathological processes.[1–3] Deglycosylation is the removal of a glycosyl residue from a glycoconjugate as mediated by glycosidases, which are conserved in almost all eukaryotes. In human cells, they mainly distribute in the endoplasmic reticulum (ER), Golgi apparatus and lysosomes.[4,5] Glycosidases localized in the ER and Golgi apparatus are responsible for tailoring the *N*-glycans on proteins after translation, and lysosomal glycosidases are known to hydrolyze the glycosyl residues on glycoconjugates endocytosed by cells.

However, the abnormal expression of glycosidases is associated with human diseases. For example, during cell senescence, β-galactosidase (β-Gal) and α-fucosidase are overly expressed,[6,7] and the abnormally high expression of β-Gal is closely related to the tumorigenesis and metastasis of ovarian cancer.[8] In addition, a recent proteomics study suggests that the expression level of cytoplasmic β-glucocerehrosidase in liver cancer tissues is significantly lower than that in para-carcinoma tissues.[9] As a consequence, the effective detection of glycosidase activities is important for glycobiological studies and disease diagnosis.

The current approaches for analysis of glycosidase activity mainly rely on colorimetric assays, which use glycosylated indicators such as 4-nitrophenol as the colorimetric substrate. However, assays that are dependent on color changes are easily compromised by the intrinsic color of the sample itself and are generally of low sensitivity. To overcome these issues, activatable fluorescent probes that exhibit a "turn-on" fluorescence upon enzymatic hydrolysis have been developed.[10–17] Based on a variety of fluorescent dyes, molecular probes capable of sensing glycosidases in cells and *in vivo* with emission wavelengths that range from the visible to the near-infrared region, have been synthesized in recent years.[18–27]

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†Electronic supplementary information (ESI) available: Additional figures, experimental section and original spectral copies of new compounds. See DOI: https://doi.org/10.1039/d3qo00605k

Here, we report the construction of a ratiometric fluorescent probe that exhibits a large Stokes shift of the fluorescence emission wavelength upon hydrolysis by glycosidases based on the combination of excited-state intramolecular proton transfer (ESIPT) and solid-state luminescence enhancement (SSLE).[28–30] The probe is a typical SSLE system when glycosylated, and after deglycosylation, the ESIPT process is activated, thereby achieving a ~140 nm red-shift in fluorescence emission.

To construct the ratiometric glycosidase probe, we first synthesized a fluorescent reporter with dual photophysical mechanisms. In the *ortho* position relative to the phenol group of tetraphenylethylene (TPE), benzothiazole (BT) was introduced. The resulting conjugate (**TPE-BT**) formed by the cycloaddition of 2-hydroxy-5-(1,2,2-triphenylethenyl)-benzaldehyde and 2-aminothiophenol exhibits ESIPT due to the intramolecular hydrogen bonding interaction between the nitrogen atom and the phenolic proton.[31,32] Then, galactose was introduced to the phenolic site to inhibit ESIPT by removing the hydrogen-bond donor. A benzyl group was used to connect the **TPE-BT** and galactose (producing the **Gal-TPE-BT** probe) in order to enhance the sensitivity for glycosidases.[33] After deglycosylation, the benzyl moiety undergoes a "self-immolation" process resulting cleavage (Fig. 1), thereby recovering the ESIPT nature of **TPE-BT**. The synthetic details for the probe are shown in Scheme S1.†

With the probe in hand, we evaluated its photophysical properties in the absence and presence of β-Gal. β-Gal isolated from *Escherichia coli* was used as a model enzyme for the analysis. We first determined that **Gal-TPE-BT** exhibited typical SSLE properties. The fluorescence of the probe (excited at 360 nm) was negligible in dimethyl sulfoxide (DMSO) as the good solvent, whereas a gradual increase in the H_2O fraction of the solvent system led to a gradual fluorescence enhancement at λ_{max} = 470 nm, which is characteristic of TPE (Fig. 2a and b). The fluorescence of the probe dropped slightly in pure water, which is common for TPE-based fluorogens.[34] This

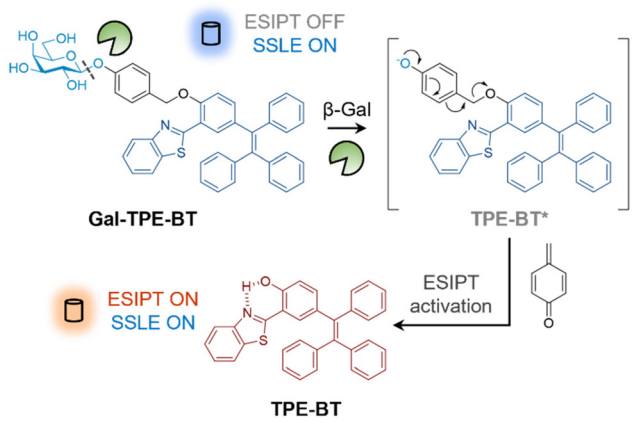

Fig. 1 Schematic illustration of the ratiometric detection of β-galactosidase based on excited-state intramolecular proton transfer (ESIPT) and solid-state luminescence enhancement (SSLE).

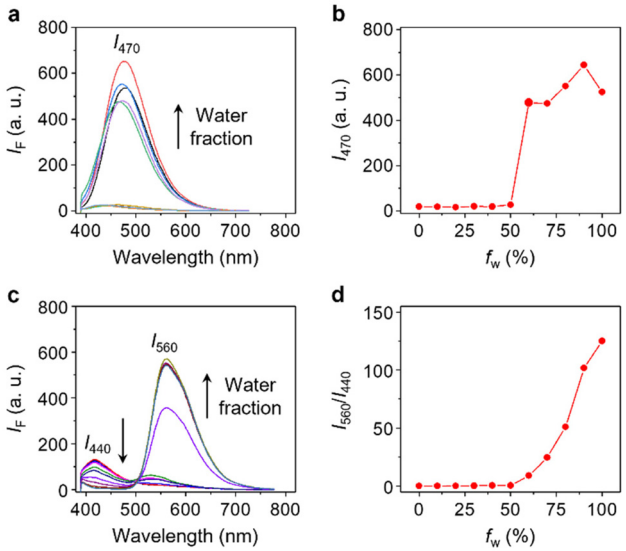

Fig. 2 Fluorescence emission spectra of (a) **Gal-TPE-BT** (10 μM) and (c) **TPE-BT** (10 μM) in DMSO with increasing water fractions. (b) Plotting the maximum fluorescence emission intensity of **Gal-TPE-BT** at 470 nm in a mixed solvent of H_2O/DMSO as a function of water fraction (f_w). (d) Plotting the ratios of the maximum fluorescence emission intensity of **TPE-BT** at 560 nm and 440 nm in a mixed solvent of H_2O/DMSO as a function of water fraction (f_w). The excitation wavelength used for **Gal-TPE-BT** and **TPE-BT** is 360 nm.

suggests the successful suppression of the ESIPT process in **Gal-TPE-BT** through the masking of the phenolic proton.

In the presence of β-Gal, the fluorescence emission spectra of **Gal-TPE-BT** in mixed H_2O/DMSO solvents changed substantially (Fig. 2c). We observed a new red-shifted emission band with λ_{max} at 560 nm that was sharply enhanced as the water fraction increased, and the original emission band with λ_{max} at 440 nm gradually decreased. The newly emerged emission band is assignable to the keto-state emission of **TPE-BT**,[31] suggesting the recovery of the ESIPT mechanism of the probe.[35,36] More interestingly, the gradually enhanced fluorescence at λ_{max} = 560 nm with increasing water fraction suggests the maintenance of the SSLE mechanism in **TPE-BT**, which favours sensing applications in an aqueous phase.

To confirm the enzymatic hydrolysis, mass spectroscopic (MS) analysis generated a MS peak assignable to **TPE-BT** detected after treatment of **Gal-TPE-BT** with β-Gal (Fig. S1†), corroborating that the galactosyl substrate can be deglycosylated by the enzyme. We also determined that the ratiometric fluorescence changes (I_{560}/I_{440}) of the probe were dependent on the concentration of β-Gal (Fig. 3a), and a good linearity from 1–6 U mL^{-1} was determined (Fig. 3b). The limit of detection of the probe for β-Gal was determined to be 0.03 U mL^{-1} ($3\sigma/k$, where σ is the standard deviation of ten blank samples, and k is the linear slope of the ratiometric changes of the probe as a function of β-Gal concentration). In addition, a kinetic study indicated a 13.5-fold increase in the I_{560}/I_{440} ratio after the reaction between the probe and the enzyme for 300 min (Fig. S2a and b†), and the K_m and V_{max} were deter-

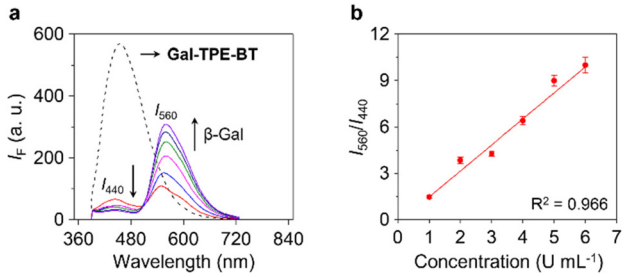

Fig. 3 (a) Fluorescence emission spectra of **Gal-TPE-BT** (10 μM) incubated with increasing concentrations of β-Gal (0–6 U mL^{-1}) for 2 h. (b) Plotting the ratios of the maximum fluorescence emission intensity of **Gal-TPE-BT** (10 μM) after treatment with increasing concentrations of β-Gal (1–6 U mL^{-1}) for 2 h at 560 nm and 440 nm as a function of β-Gal concentration (error bars mean S. D., n = 3). All measurements were performed in a solvent mixture of phosphate buffered saline (PBS) (0.01 M, pH 7.4)/DMSO (7 : 3, v/v) with an excitation of 360 nm.

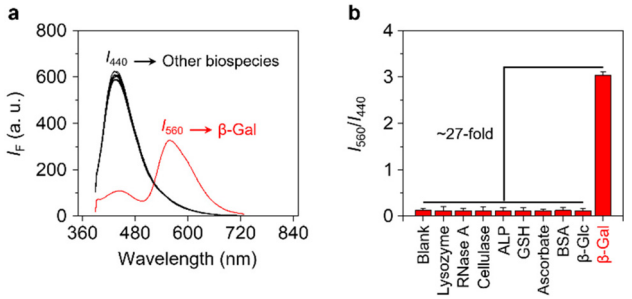

Fig. 4 (a) Fluorescence emission spectra of **Gal-TPE-BT** (10 μM) in the presence of β-Gal (5 U mL^{-1}) and other biospecies including lysozyme (5 U mL^{-1}), ribonuclease A (RNase A) (5 U mL^{-1}), cellulase (5 U mL^{-1}), alkaline phosphatase (ALP) (5 U mL^{-1}), γ-glutathione (GSH) (100 μg mL^{-1}), ascorbate (100 μg mL^{-1}), bovine serum albumin (BSA) (100 μg mL^{-1}) and a β-glucosidase (β-Glc) (5 U mL^{-1}). (b) Plotting the ratios of the maximum fluorescence emission intensity of **Gal-TPE-BT** (10 μM) of the different analytes. All measurements were performed in a solvent mixture of phosphate buffered saline (PBS) (0.01 M, pH 7.4)/DMSO (7 : 3, v/v) with an excitation of 360 nm.

mined to be 27 μM and 0.04 μM s^{-1}, respectively, from the Lineweaver–Burk plots (Fig. S2c and d†). We also measured the K_m and V_{max} of a commercial fluorescent β-Gal probe, 4-methylumbelliferyl-β-D-galactoside (**4-MU-β-Gal**) (Fig. S3†). The ~twofold smaller K_m of **Gal-TPE-BT** (27 μM) than that of **4-MU-β-Gal** (48 μM) suggests a higher affinity of our probe for the enzyme.

Next, we studied the morphological changes of **Gal-TPE-BT** before and after the enzymatic reaction by high-resolution transmission electron microscopy (HRTEM). In its representative TEM images (Fig. S4†), we observed tube-like structures of **Gal-TPE-BT**, and after addition of β-Gal, aggregated particles began to emerge. In addition, DLS (dynamic light scattering) used showed that the hydrodynamic parameter of the probe after reaction with β-Gal was much larger than that of **Gal-TPE-BT** without the treatment of β-Gal (Fig. S5a†). These results corroborate the SSLE property of the probe before and after treatment of the enzyme. The critical micelle concentration (CMC) of the probe was determined to be 5.2 μM (Fig. S5b†), and subsequent DLS and fluorescence analyses by continuously incubating the probe in PBS for 60 h suggest the good colloidal stability of **Gal-TPE-BT** (Fig. S5c and d†).

Finally, we evaluated the selectivity of **Gal-TPE-BT** with a range of different biological species (Fig. 4a and b). We determined that the presence of unselective enzymes including lysozyme, ribonuclease A (RNase A), cellulase and alkaline phosphatase (ALP), and biologically relevant species including γ-glutathione (GSH), vitamin C (VC) and bovine serum albumin (BSA) did not cause the fluorescence emission of the probe to change. More importantly, the treatment of **Gal-TPE-BT** with a β-glucosidase (β-Glc) that hydrolyzes glucose, which is the C4-epimer of galactose similarly caused minimal fluctuation in fluorescence of the probe. These results suggest the good selectivity of **Gal-TPE-BT** for β-Gal sensing.

To conclude, the incorporation of both ESIPT and SSLE mechanisms into a single molecular probe led us to achieve the ratiometric detection of β-Gal activity over a range of other enzymes. The large Stokes shift associated with the probe makes it a promising tool for the unbiased analysis of glycosidase activities in diagnostic and drug-screening assays. This research also paves the way for the design of sensitive fluorescent probes for the detection of other enzymatic activities based on mixed photophysical mechanisms.[37–41]

Conflicts of interest

The authors have no conflicts of interest to declare.

Acknowledgements

The authors thank the Natural National Science Foundation of China (no. 91853201, 92253306 and 82151219), the Shanghai Municipal Science and Technology Major Project (no. 2018SHZDZX03), the Fundamental Research Funds for the Central Universities (222201717003), the Programme of Introducing Talents of Discipline to Universities (B16017) and the Open Funding Project of the State Key Laboratory of Bioreactor Engineering. TDJ wishes to thank the Open Research Fund of the School of Chemistry and Chemical Engineering, Henan Normal University for support (2020ZD01). The Research Center of Analysis and Test of East China University of Science and Technology is gratefully acknowledged for assistance in analytical experiments.

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