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Water soluble triazolopyridiniums as tunable blue light emitters†‡

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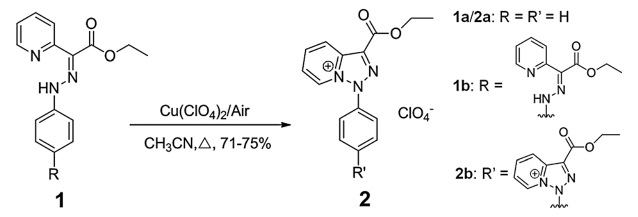
Two [1,2,3]triazolo[1,5-*a*]pyridinium salts have been prepared *via* a novel Cu(II)-mediated oxidative cyclization reaction. Both water soluble compounds exhibit broad-range fluorescence emission with huge Stokes shifts as well as color tunability.

Blue light fluorophores have attracted much attention because of their importance in Förster resonance energy transfer (FRET)[1] and OLED applications.[2] The development of such fluorophores has been limited by the large energy gap required between the excited- and ground-state energy levels, which can decrease quantum yields and lower photostability.[3] [1,2,3]Triazolo[1,5-*a*]pyridines[4] are an important class of blue light emitting bicyclic pyridines that have been widely studied and used as synthetic intermediates, metal ligands and chemosensors.[5] These systems usually have large Stokes shifts that impede self-quenching and interference from scattered light, which are important properties in biological applications.[6] However, these fluorphores have the same intrinsic shortcoming as most π-conjugated fluorophores, namely poor water solubility. This limitation has to be overcome if such systems are to be used for bioassay or imaging applications. One solution to this problem is the introduction of solubilizing groups; this strategy, however, usually leads to synthetic complications that could be avoided if the systems are rendered to be intrinsically water soluble. We hypothesized that one way of accomplishing this might be the use of the positively charged counterparts of these systems, namely [1,2,3]triazolo[1,5-*a*]pyridinium salts.[7] These compounds although discovered in 1952, have received very little attention, except for a few cases in which they were used as reactive intermediates.[8] Herein we report the novel and convenient synthesis of water soluble [1,2,3]triazolo[1,5-*a*]pyridinium salts *via* Cu(II)-mediated oxidative cyclization, and their interesting photophysical properties comprising of tunable blue light emissions with "mega" Stokes shifts.[9]

The synthesis of [1,2,3]triazolo[1,5-*a*]pyridinium salts has been previously accomplished *via* oxidative cyclization of appropriate hydrazones using various oxidants: $Pb(OAc)_4$,[7] *N*-bromosuccinimide (NBS),[10] 2,4,4,6-tetrabromocyclohexa-2,5-dienone (TBB)[11] and antimony(V) chloride ($SbCl_5$).[12] The use of electrochemical ring closure was also reported.[13] However, these reagents/methods all have their own drawbacks. For example, NBS and TBB also lead to bromination resulting in mixtures of products[8c] and $SbCl_5$ is toxic. We have recently found that Cu(II) in acetonitrile (CH_3CN) can be used as the oxidant for the synthesis of triazolopyridiniums from our hydrazone-based molecular switches.[14] This oxidation takes place under aerobic conditions to yield the appropriate triazolopyridiniums in high yields (Scheme 1). Significantly, no reaction is observed when the solvent is switched from CH_3CN to either methanol or acetone, which can be attributed to the enhanced oxidizing ability of Cu(II) in CH_3CN.[15]

Compounds **2a** and **2b** were characterized using NMR spectroscopy (Fig. S9, S10, S13 and S14, ESI‡). The ^1H NMR spectrum of **2a** shows that all the aromatic signals are shifted downfield relative to the parent hydrazone, which is consistent with the development of a positive charge in the pyridyl ring.[14] This effect is more pronounced in **2b**, where the phenyl proton signal is shifted downfield to 8.33 ppm as opposed to 7.38 ppm in **1b**. Moreover, the spectrum does not contain the hydrazone



Scheme 1 The synthesis of [1,2,3]triazolo[1,5-*a*]pyridinium salts **2a** and **2b**.

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‡ Electronic supplementary information (ESI) available: Experimental procedures, NMR spectra, UV-vis spectra, fluorescence spectra, computational methods and crystal structral data for compound **1b**. CCDC 887676. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2cc34976k

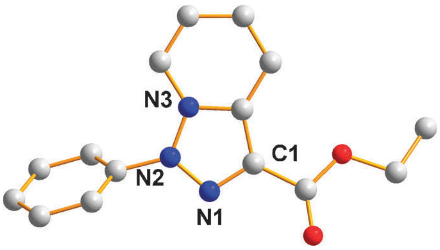

Fig. 1 Ball-stick drawing of the crystal structure of **2a**. All hydrogen atoms and the ClO_4^- counterion are omitted for clarity.

Table 1 A summary of the photophysical properties of **2a** and **2b** in H_2O^a

	Abs. λ_{max} (ε)	Fl. λ_{em} (Φ^b)	Stokes shift	FWHM
2a	302 (11 100)	469 (0.05)	167/11 790	131/6008
2b	311 (22 100)	412 (0.30)	101/7882	94/5097

[a] Abs. λ_{max} and Fl. λ_{em} are reported in nm, and the extinction coefficient ε is calculated in L mol^{-1} cm^{-1}. Stokes shifts and FWHMs are reported in both nm and cm^{-1}. [b] ±0.02.

N–H proton, which is an indication that the oxidative cyclization has taken place. The crystal structure of **2a** confirms the formation of the triazolopyridinium ring (Fig. 1).§ To the best of our knowledge this is the first reported crystal structure of a triazolopyridinium compound. The newly formed ring system is perfectly planar, and the distance between the N2 and N3 atoms is 1.364(2) Å, which is slightly longer than that in the neutral triazolopyridine (1.351(4) Å).[16] The C1–N1 bond length is 1.324(2) Å, longer than in hydrazone **1a** (1.305(2) Å), but still within the C=N double bond range. The phenyl substituent at position 2 is not coplanar with the triazolopyridinium ring, and the dihedral angle between them is 63.40(5)°. This is in sharp contrast with the coplanar hydrazone **1a**,[14d] or 2-substituted [1,2,3]triazoles,[17] in which the aryl substituents are usually coplanar or have very small dihedral angles with the triazole cores. Since no significant intermolecular interactions were observed in the extended structure, the large dihedral angle can be attributed to the electronic structure in N2.

Both **2a** and **2b** have good solubility in water and polar organic solvents, such as acetone, CH_3CN and EtOH. The UV/Vis spectra of **2a** and **2b** show absorption maxima (λ_{max}) around 300 nm (Fig. 2), and no appreciable solvatochromism is observed for both compounds (Fig. S1 and S2, ESI‡). It is noteworthy that the extinction coefficient of **2b** at λ_{max} is more than double that of **2a**. Considering the fact that the triazolopyridinium ring is not in conjugation with the phenyl ring, the increase in extinction coefficient in **2b** most probably results from the contribution of the additional triazolopyridinium unit. The H_2O solution of **2a** emits green-blue light upon exicitation at 300 nm with a quantum yield of 0.05 ± 0.02, whereas **2b** emits deep blue light with a much higher quantum yield (0.30 ± 0.02). The more than eight fold enhancement in quantum yield from **2b** to **2a** is much more significant than the increase in extinction coefficient. On one hand, **2b** has one additional fluorophore than **2a**. On the other hand, since the non-conjugated phenyl ring is able to quench fluorescence *via* charge transfer,[18] the introduction of a second electron-withdrawing triazolopyridinium unit in **2b** can help reduce its quenching effect leading to the increase in quantum yield. For comparison, we also studied the photophysical properties of **2a** and **2b** in CH_3CN, and found that they are almost identical to those in H_2O (Fig. S3, ESI‡).

Careful examinations of the emission spectra of **2a** and **2b** reveal several interesting photophysical properties (Table 1). Both compounds have very broad emission profiles, spanning over the visible range, especially **2a** that spans from 370 nm to over 600 nm. Furthermore, the full widths at half maximum (FWHM) for both comopounds are as large as about 100 nm or 5000 cm^{-1}. Both **2a** and **2b** exhibit mega Stokes shifts (above 100 nm, or around 100 000 cm^{-1}), which is not a common phenomenon for simple organic dyes.[9] As mentioned before, this property is important for preventing self-quenching and light scattering. The CIE (Commission internationale de l'éclairage) 1931 color space chromaticity diagram was used to determine the color of the missions, and the results show that from **2a** to **2b**, the color goes from green-blue (0.159, 0.232) to deep blue (0.159, 0.094), demonstrating the color tunability of the triazolopyridinium compounds (Fig. S4, ESI‡).

We performed time-dependent density functional theory (TDDFT) calculations on models of **2a** and **2b** (Fig. S5, ESI‡) to elucidate the quantum mechanical origins of the triazolopyridinium UV/Vis and fluorescence spectra. The computations utilized the PBE density functional,[19] a triple-zeta basis set,[20] and the COSMO continuum solvation model as implemented within ORCA 2.9.1.[21] Based upon the TDDFT results, the electronic transitions responsible for the prominent UV/Vis transitions near 380 nm can be described as HOMO→LUMO transitions (Fig. S6, ESI‡).[22] Consistent with the experiment, TDDFT predicts that the extinction coefficient for **2b** is approximately triple that of **2a**. Inspection of the MOs involved in these transitions provides an explanation for the relative intensities of this band in **2a** and **2b** (Fig. 3). In both cases, the HOMO is antibonding with respect to the triazolopyridinium–phenyl bond. For **2a** the LUMO is a triazolopyridinium-based mixture of triazolopyridinium and phenyl π-orbitals, whereas the LUMO is a phenyl-based mixture of the same two orbitals in **2b**. Consequently, there is a better

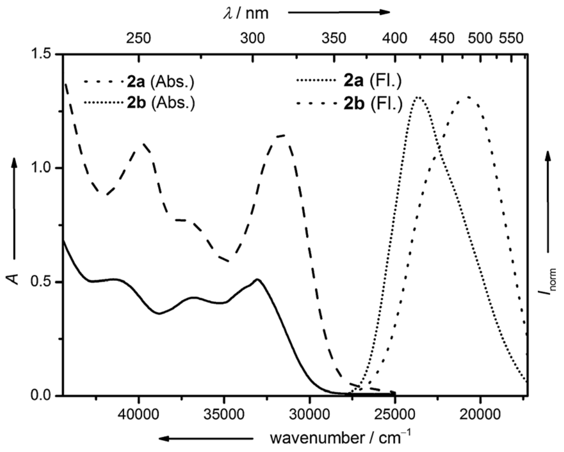

Fig. 2 The UV/Vis absorption (5.0 × 10^{-5} M) and normalized emission spectra of **2a** and **2b** in H_2O.

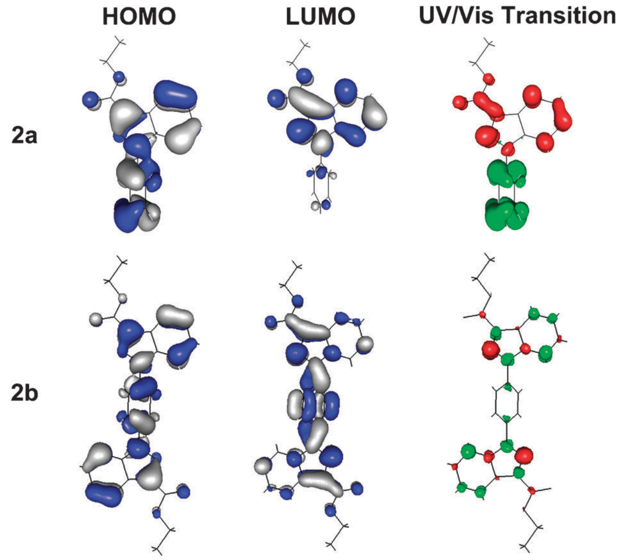

Fig. 3 COSMO/PBE/TZVP TDDFT-computed HOMO, LUMO, and TDDFT difference densities of **2a** and **2b** in H_2O. Green indicates a loss of electron density upon excitation at 380 nm, and red indicates a gain of electron density.

orbital overlap of the HOMO and LUMO in **2b** compared to **2a**, resulting in a more intense UV/Vis transition.

The TDDFT calculations also clarify the origin of the broad bandshapes in the UV/Vis and fluorescence spectra of **2a** and **2b**. One way to visualize the electron density redistribution in the excited state is a TDDFT difference density difference plot (Fig. 3). This plot shows that the UV/Vis transition in **2a** has significant charge transfer character with electron density being donated by the phenyl substituent to the triazolopyridinium unit. In contrast, the altered LUMO in **2b** means that the UV/Vis transition in this compound may be better described as a $\pi \rightarrow \pi^*$. Consequently, we expect significant differences between the triazolopyridinium and phenyl π-bond strengths in the ground and excited electronic states, especially for the charge transfer transition of **2a**. These perturbations of the triazolopyridinium and phenyl π-systems are expected to introduce a significant vibronic structure into the UV/Vis and fluorescence bands, which is apparently unresolved in the room temperature UV/Vis and fluorescence spectra of **2a** and **2b**.

In summary, we have shown the synthesis of two new [1,2,3]triazolo[1,5-*a*]pyridinium salts from 2-pyridylphenylhydrazones *via* a novel Cu(II)-mediated oxidative ring clousure reaction. The synthesized mono-(**2a**) and bis-(**2b**) triazolopyridiums are water soluble, show blue fluorescence, possess broad emission profiles and exhibit mega Stokes shifts. Since the positive charge center of the triazolopyridinium ring can be susceptible to nucleophilic attack,[8c,23] these compounds can be promising in terms of anion sensing, which is currently being looked into.

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Notes and references

§ Crystal data of **2a:** $C_{15}H_{14}ClN_3O_6$, M = 367.74, monoclinic, a = 13.7923(7), b = 5.9508(3), c = 19.9335(11) Å, U = 1608.44(15) $Å^3$, T = 173(2) K, space group $P2_1/c$ (no.14), Z = 4, 24909 reflections measured, 2947 unique (R_{int} = 0.0287) which were used in all calculations. The final $R\omega$ ($F2$) was 0.1178 (all data).

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