

Fluorescent ‘Twist-on’ Sensing by Induced-Fit Anion Stabilisation of a Planar Chromophore

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Rigidly preorganised receptors for anionic, cationic and molecular guests exhibit high binding constants and high selectivity. Such characteristics are desirable in the design of high-specificity molecular sensors. However, because there is no change in conformation between free and bound host, any change in observable characteristics such as fluorescence emission must result from the electronic effects of the bound guest.^[1] In contrast flexible systems allow the possibility of induced fit^[2] sensing, in which the binding event brings sensing moieties into close mutual proximity. For example binding-induced conformational change can cause close mutual proximity of fluorophores resulting in excimer formation^[3] or may change the degree of twist in a conjugated aromatic system, altering its photophysical properties.^[4,5] Similarly, conformational changes may result in changes to the electrochemical properties of redox-active sensing units.^[6] However, flexible receptors are often less selective and exhibit lower overall affinities compared to their more rigid analogues.^[7] With careful molecular design it should be possible to reduce the number of conformational degrees of freedom of a receptor such that binding of a specific anion results in a well-defined induced-fit process involving only a single bond rotation, thus combining the benefits of rigid preorganisation and induced-fit sensing. We now report the realisation of this concept in a neutral, rigid dialkyne based anion receptor.^[8]

The diphenylacetylene unit and its longer congener diphenylbutadiyne have interesting photophysical properties.

Both compounds exhibit low quantum yield of fluorescence due to the presence of a non-emissive ¹A_{1u} state (a $\pi_y^* \leftarrow \pi_x$ transition), which lies close in energy to the emissive ¹B_{1u} state ($\pi_x^* \leftarrow \pi_x$ transition). Excited state population transfer to the non-emissive ¹A_{1u} state from the emissive ¹B_{1u} state results in low emission and is an activated process.^[9] By coupling the diarylalkyne unit to *ortho* anion binding substituents as in **1**, we obtain rigid bis(urea)-based molecular ‘tweezers’,^[10] which in the case of **1** have an anion binding site of suitable size that is almost exactly complementary to chloride. The accessibility of the ‘dark’ ¹A_{1u} state depends significantly on the angle of rotation about the alkyne unit.^[11] If anion binding can be used to induce a planar conformation in the molecule this should disfavour the relocation of excitation from the *x* to the *y* plane and hence ‘turn on’ the emission.

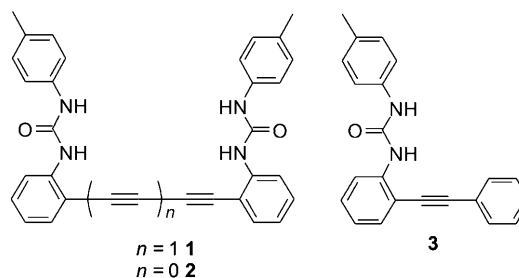
Compound **1** was prepared by an Eglinton reaction using copper(II) acetate as catalyst.^[12] Two control compounds **2** and **3** were also prepared for comparison using Sonogashira cross-coupling of 2-iodoaniline with 2-ethynylaniline and phenyl acetylene respectively, followed by reaction with *p*-tolyl isocyanate (see Scheme 1 and the Supporting Information).^[13]

DFT calculations (B3LYP/6-311G(d,p)) on **1** show that a twisted (and hence non-emissive) geometry, in which the urea groups are well-separated, is more stable than an eclipsed structure by approximately 3 kJ mol^{−1} with an ex-

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Scheme 1. Fluorescent receptor **1** and model compounds **2** and **3**.

ceptionally low rotational barrier between the two conformers (determined by DFT calculations and consistent with related systems; Figure 1a).^[14] Interestingly the calculations

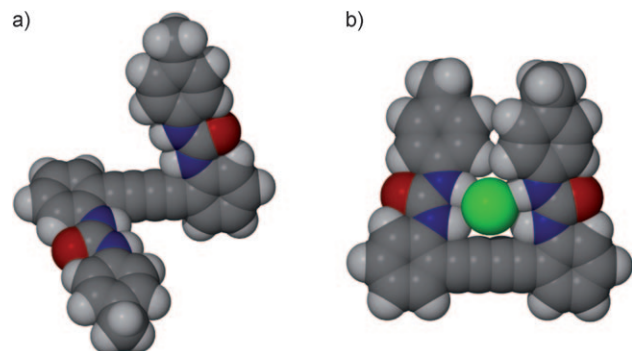


Figure 1. a) DFT-optimised geometry of free **1**; b) DFT-optimised geometry of **1**·Cl[−].

also suggest a degree of preorganisation arising from intramolecular CH $\cdots$ O and NH $\cdots$ π (alkyne) interactions that favour the positioning of the urea NH groups over the central alkyne unit. This conformational feature is also observed in the X-ray crystal structure of the DMSO disolvate of the receptor (Figure 2). The X-ray structure shows a planar *transoid* geometry with NH $\cdots$ O hydrogen bonding interactions to the DMSO guest molecules which are therefore positioned adjacent to the alkyne moieties.

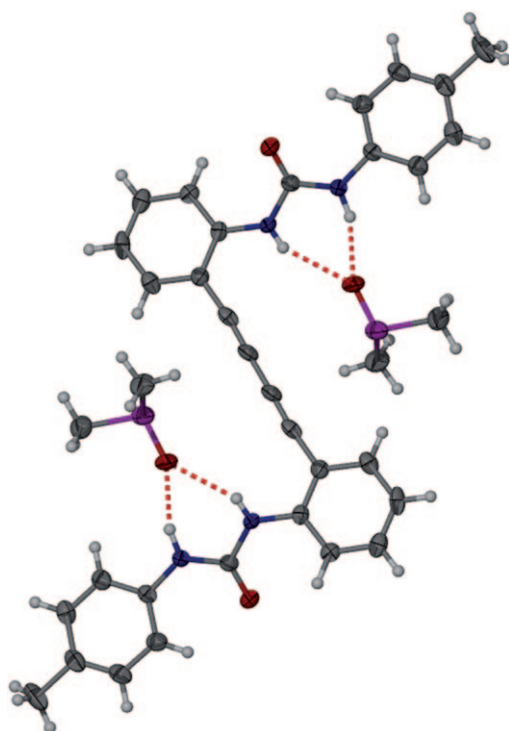


Figure 2. X-ray crystal structure of **1**·2DMSO (ellipsoids 50 %).^[15]

Compound **1** binds chloride (as the NBu₄⁺ salt) in CHCl₃/DMSO (70:30) solution in a 1:1 host anion ratio with log K_{11} = 2.557(5) (determined by ¹H NMR spectroscopic titration, Table 1). The 1:1 stoichiometry was confirmed by Job

Table 1. Anion binding constants for receptors **1–3** in CHCl₃/DMSO (70:30) solution.

Anion	Receptor, log β		
	1	2	3
Cl [−]	2.557(5)	1.831(7)	<1
Br [−]	1.56(1)	<1	<1
I [−]	<1	<1	<1
F [−]	log β_{11} 4.01(6)	log β_{11} 4.09(6)	log β_{11} 2.45(3)
MeCO ₂ [−]	log β_{12} 5.58(6)	log β_{12} 6.58(5)	log β_{21} 5.21(9)
	3.61(1)	2.993(6)	log β_{11} 2.41(4)
			log β_{21} 5.11(9)
NO ₃ [−]	<1	<1	<1
H ₂ PO ₄ [−]	4.29(5)	3.29(1)	log β_{11} 2.01(2)
HSO ₄ [−]	1.61(1)	1.2888(1)	log β_{21} 4.60(4) <1

plot and can be readily explained by the binding of the anion in between the two urea functionalities as shown in the DFT optimised model (Figure 1b). The fact that K_{11} for **1** is significantly greater than for compound **2** and control compound **3** highlights the high degree of complementarity between the bis(urea) binding site and Cl[−]. The affinity for the larger bromide anion is very significantly less than that for chloride, highlighting the high degree of size selectivity, while iodide is not bound at all.

The fluorescent emission of **1** in CHCl₃/DMSO (95:5) is very low with a quantum yield of 0.0063 (see supplementary information for methods). This value is consistent with that observed for diphenylbutadiyne. Addition of chloride (as the tetrabutyl ammonium salt) to **2** results in only a small change in the emission intensity (enhancement by a factor of 2), however, chloride binding by **1** gives a dramatic increase in fluorescence quantum yield to 0.033 (a five-fold enhancement). In contrast, binding of other anions, often with stronger binding than chloride, does not result in the same degree of fluorescence enhancement, Figure 3.

The addition of fluoride and acetate to **1** results in a initial increase in fluorescence emission. However further addition of anion reduces the emission to almost the initial intensity. ¹H NMR spectroscopic titrations suggest that for fluoride a 1:1 and a 1:2 host:guest stoichiometry is present and is consistent with the 1:1 species causing planarisation of **1** and a turn-on response. As a second fluoride is bound, it can be imagined a twisted conformation similar to the free host is obtained and the emission is therefore reduced. In the case of acetate, 1:1 host:guest binding is observed via ¹H NMR spectroscopic titrations and Job plot, however the less competitive environment used in the fluorescence study may lead to a 1:2 host:guest stoichiometry being observed analogous to fluoride. Further investigation into this behaviour is currently in progress.

A competition study was undertaken in which acetate (as the TBA salt) was titrated into a solution of **1** with 50 equiv-

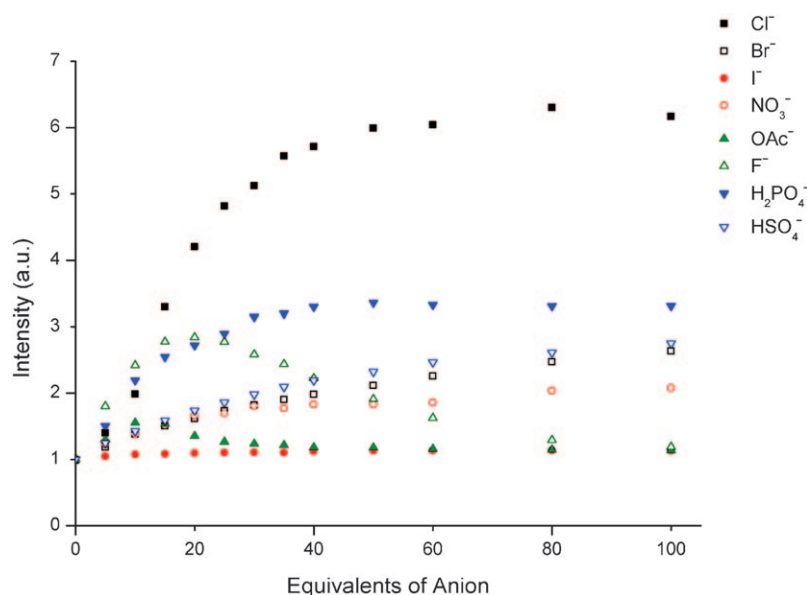


Figure 3. Fluorescence spectroscopic titration of receptor **1** with various anions in $\text{CHCl}_3/\text{DMSO}$ (95/5) solution ($1 \times 10^{-5} \text{ mol dm}^{-3}$, $\lambda_{\text{ex}} = 340 \text{ nm}$, $\lambda_{\text{em}} = 395 \text{ nm}$).

alents of TBA-Cl present. Upon addition of acetate, the intensity of emission showed a decrease in intensity, consistent with the host preferentially binding to acetate over chloride and forming a complex with low emission (see supplementary information).

The intensity of emission in tethered DPA derivatives has been shown to increase as the conformation is restricted to a more planar geometry.^[11c] This change is due to the increased activation energy of the $^1\text{A}_{1u} \rightarrow ^1\text{B}_{1u}$ internal conversion for the planar conformation. This increased activation energy results in a larger k_f (rate of fluorescence) value observed for conformationally restricted derivatives and a lower k_{nr} (rate of non-radiative excitation transfer).

The emission from compound **1** shows a biexponential decay (lifetimes of 1.97 and 0.49 ns), possibly suggesting non-exponential or complex emissive decay processes. Both of these values reduce upon addition of chloride (*cf.* 1.01 and 0.15 ns). Given the increase in quantum yield of fluorescence upon addition of chloride, this suggests an increase in k_f and a decrease in k_{nr} , consistent with the planarisation of the chromophore and an increase in the activation energy of internal conversion.

In order to further understand the origins of this behaviour a series of time dependent DFT calculations were undertaken using the recently developed Coulomb attenuated extension of the B3LYP functional, CAM-B3LYP.^[16] The 6-311G(d,p) basis was used on all atoms for **1**, and augmented for **1**·Cl[−] with the 6-311+G(d) on Cl, and an additional diffuse set of s, p and d functions added to each peripheral hydrogen atom. In the case of free **1**, the $\text{S}_1 \leftarrow \text{S}_0$ transition is strongly allowed (a $\pi_x^* \leftarrow \pi_x$ transition) and would appear to be responsible for the observed emission in the free host. There is a low-lying accessible dark state ($\pi_y^* \leftarrow \pi_x$) which crosses with the populated $\pi_x^* \leftarrow \pi_x$ state at twisted geometries.

For example at the *trans* conformation the bright S_1 state is only 0.03 eV lower than the dark $\pi_y^* \leftarrow \pi_x$ state, Figure 4a. This excited surface crossing is further confirmed by complete active-space self-consistent field (CASSCF) calculations on diphenylbutadiyne, which show that the $\pi_x^* \leftarrow \pi_x$, and $\pi_y^* \leftarrow \pi_x$ electronic states form the components of a degenerate state at *fully twisted* (D_{2d}) geometries. Thus, there exists a Jahn–Teller conical intersection (that facilitates very efficient radiationless population transfer between such states. Thus, in **1** excitation drives the system towards a region of surface crossing and the optically dark state becomes populated. In contrast, in **1**·Cl[−], the binding-enforced planarity of the chloride complex means the two states are ~0.5 eV apart and population transfer cannot readily occur, Figure 4b.

In conclusion, a carefully designed conformational fluorescent switch anion receptor has been realized, which allows an induced fit approach to binding. The addition of chloride results in the planarisation of the chromophore and hence an increase in the energy of the non-emissive dark state. This results in a significant increase in the fluorescence emission from the receptor.

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Keywords: anion binding • luminescence • sensors • supramolecular chemistry • urea

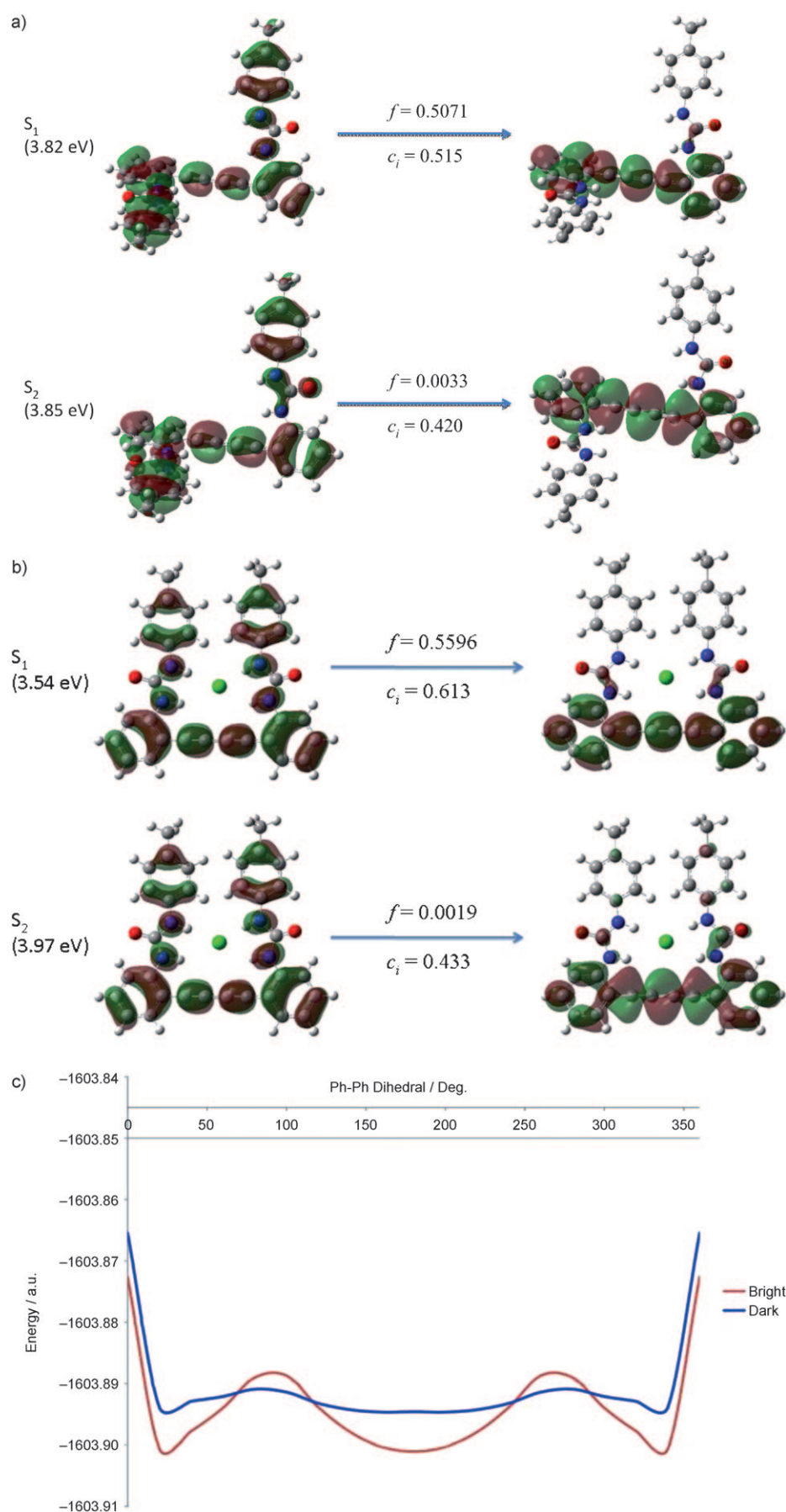


Figure 4. Principal components of relevant low-lying electronic states giving rise to the fluorescence (S_1) and non-radiative decay (S_2) as obtained from TD-DFT computations (f oscillator strength of transition, c_i coefficient of orbital transition in response eigenvector) for (a) free host in *cisoid* geometry and (b) optimised **1**-Cl[−] complex. (c) unrelaxed scan across the alkyne dihedral angle for the bright and dark states.

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- [15] Crystal data for Compound **1**: C₃₆H₃₈N₄O₄S₂, *M* = 654.82, yellow plate, 0.15 × 0.10 × 0.02 mm³, monoclinic, space group *P*2₁/*c* (No. 14), *a* = 15.6775(11) Å, *b* = 6.1785(5) Å, *c* = 17.4171(12) Å, β = 96.985(2)°, *V* = 1674.6(2) Å³, *Z* = 2, ρ_{calc} = 1.299 g cm^{−3}, *F*₀₀₀ = 692, SMART 6 K, MoKα radiation, λ = 0.71073 Å, *T* = 120(2) K, 2θ_{max} = 50.0°, 19711 reflections collected, 2948 unique (*R*_{int} = 0.1772). Final GooF = 0.986, *R*₁ = 0.0605, *wR*₂ = 0.1350, *R* indices based on 1483 reflections with *I* > 2σ(*I*) (refinement on *F*²), 217 parameters, 0 restraints. Lp and absorption corrections applied, μ = 0.204 mm^{−1}.
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