View Article Online View Journal

Photochemical & Photobiological Sciences

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: A. Harriman, D. Sirbu, O. D. Woodford and A. benniston, *Photochem. Photobiol. Sci.*, 2018, DOI: 10.1039/C8PP00162F.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the **author guidelines**.

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard <u>Terms & Conditions</u> and the ethical guidelines, outlined in our <u>author and reviewer resource centre</u>, still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.



rsc.li/pps

ARTICLE

CONTRACTOR CONTRACTOR

Photocatalysis and Self-catalyzed Photobleaching with Covalently-Linked Chromophore-Quencher Conjugates Built Around BOPHY

Dumitru Sirbu, Owen J. Woodford, Andrew C. Benniston and Anthony Harriman*

Received 00th January 20xx, Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

Two Chromophore-Quencher Conjugates (CQCs) have been synthesized by covalent attachment of the anti-oxidant dibutylated-hydroxytoluene (BHT) to a pyrrole-BF₂ chromophore (BOPHY) in an effort to protect the latter against photofading. In fluid solution, light-induced intramolecular charge transfer is favoured in polar solvents and helps to inhibit photo-bleaching of the chromophore. The rate of photo-fading, which scales with the number of BHT residues, is zero-order in polar solvents but shows a linear dependence on the number of absorbed photons. The zero-order rate constant shows an inverse correlation with the fluorescence quantum yield measured in the same solvent. Photo-bleaching in benzonitrile involves autocatalysis while reaction in cyclohexane shows an unexpected stoichiometry. NMR spectroscopy indicates initial damage takes place at the BHT unit and allows identification of a reactive hydroperoxide as being the primary product. In the presence of an adventitious substrate, this hydroperoxide is a photocatalyst for amide formation under mild conditions.

Introduction

Published on 25 April 2018. Downloaded by University of New England on 30/04/2018 17:32:25

Organic dyes tend often to degrade when subjected to prolonged exposure to white light. A common cause of such photo-fading is the transient formation of a triplet-excited state that reacts with molecular oxygen to form the highly reactive species known as singlet oxygen.¹ The latter attacks unsaturated cyclic structures² and, although short lived in most solvents,3 reacts irreversibly to bleach the dye. However, inhibiting intersystem-crossing to the triplet manifold does not always eliminate photo-bleaching⁴ and it is clear that degradation of the chromophore can occur through other types of photochemistry. Some relief can be obtained by systematic engineering of the sample, including removal of oxygen, embedding in plastic and/or incorporation of filters. Addition of stabilizers or anti-oxidants can also be considered as a means to prolong the duty cycle of the chromophore. A somewhat similar approach is found in natural photosynthesis where carotenoids deactivate triplet-excited states⁵ and remove oxy-radicals.⁶ Indeed, in the light-harvesting antennae of green plants and photosynthetic bacteria, β-carotene is employed as an anti-oxidant at very high concentration but this strategy is less attractive for artificial analogues.

The need for organic dyes that resist fading under illumination has been recognized for a very long time, as has been the realization that certain dyes promote the light-induced degradation of fabrics and other supporting media.⁷ This led to

the early classification of dyes as being light-fast; this refers to dves that do not fade under illumination and also cause little or no photo-tendering. The first real examination of the mechanism behind the photochemical damage caused by exposure of organic dyes to sunlight was reported by Bridge and Porter in 1958.8 Using the newly developed flash photolysis technique, these authors showed that 9,10-anthraquinone dyes formed the highly reactive n,π^* excited triplet state under illumination. This *meta*stable species abstracts a hydrogen atom from any available source, thereby promoting both loss of dye and destruction of the host. The simple strategy of adding hydroxyl groups to the 1,4positions rendered the n,π^* triplet state impotent⁹ because of intramolecular proton transfer. The reactive n, π^* triplet state can also be deactivated by substituting electron donating groups at positions where intramolecular charge transfer is strongly favoured.¹⁰ Such observation exemplify early attempts to stabilize the dye against photo-fading but the majority of lightfast dyes are identified by serendipity.

Recent advances in single-molecule microscopy¹¹ and superresolution microscopy¹² have fuelled interest in light-fast dyes. Here, there is a particular need for dyes that absorb and emit in the far-red region. Cyanine dyes, which are by far the most popular emitter used for such experiments, are well known to fade on exposure to visible light.¹³ This realisation has led to new strategies for protecting the dye against deleterious photochemical damage. For example, recent work by Cosa et al.¹⁴ has reported beneficial effects from addition of triplet quenchers that enter into light-induced electron-transfer reactions. A key feature here concerns spin conversion in the resultant geminate radical ion pairs. Related work¹⁵ has found an extended duty cycle for a conjugated polymer used in total internal reflection microscopy when certain triplet quencher additives are present. The importance of geminate recombination as a photoprotective protocol has also been stressed by Tinnefeld

^{a.} Molecular Photonics Laboratory, School of Natural and Environmental Sciences (Chemistry), Bedson Building, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kinadom

Electronic Supplementary Information (ESI) available: [includes compound characterisation, photo-polymerisation with P2B, Arrhenius and Lippert-Mataga plots, characterisation of the amide product and examples of bleaching kinetics in various solvents]. See DOI: 10.1039/x0xx00000x

View Article Online DOI: 10.1039/C8PP00162F

ARTICLE

Published on 25 April 2018. Downloaded by University of New England on 30/04/2018 17:32:25

Journal Name



Scheme 1. Illustration of the methodology used to isolate the new Chromophore-Quencher Conjugates P1B and P2B. Reagents and Conditions: (i) hydrazine hydrate, 3,5-dimethylpyrrole-2-carboxaldehyde, glacial AcOH, ethanol, RT, 1.5h; (ii) BF₃·Et₂O, DIPEA, toluene, 60 °C, 16h; (iii) 3,5-di-tert-butyl-4-hydroxybenzaldehyde, p-TsOH, piperidine, toluene, reflux to dryness twice; (iv) 1 atm. H₂, 10% Pd/C, CH₂Cl₂, CH₃OH, RT, 3h. The percentage yield is provided for each isolated compound.

*et al.*¹⁶ Here, single-molecule fluorescence spectroscopy has indicated improved levels of photostability using combinations of reagents, such as β -mercaptoethanol and Trolox. These additives quench the triplet-excited state via diffusion-limited, electron-transfer reactions. Such strategies can result in greatly improved (i.e., >5,000-fold) levels of photochemical protection, leading to dyes that can emit in excess of 10⁸ photons per molecule.¹⁷

A logical, but important, extension of the above research into the photoprotection of cyanine dyes involves direct attachment of the quencher to the chromophore. This type of covalentlylinked conjugate, where the additive is nitrobenzyl alcohol or Trolox, has been developed by Blanchard *et al.*¹⁸⁻²⁰ and shown to provide high levels of protection. Somewhat related cyanine dye derivatives have been reported²¹ to give improved (>100-fold) photostability when two or more redox-active quenchers are attached to the chromophore. These latter conjugates have been described as self-healing and, as above, the primary target is the triplet-excited state. A more general approach, applicable to dyes other than cyanines, involves linking the dye to a photostabilizer and a biomolecular target via an unnatural amino acid.²² Such materials are suitable as fluorescent labels for DNA, antibodies and proteins for use with single-molecule microscopy.

Similar conjugates but with cyclooctatetraene as appendage operate by deactivating the *meta*-stable triplet-excited state by way of intramolecular triplet-triplet energy transfer.²³ This latter system has considerable appeal because no charged species are formed as intermediates and there is less likelihood that toxic radicals will arise during reaction. Appended Trolox units appear not to act as triplet quenchers in the protective process¹⁸ and their precise role is still under investigation.^{24,25}

Here, we describe a related system whereby the cyanine dye has been replaced with a symmetrical pyrrole-BF₂ chromophore of the BOPHY class,²⁶ introduced recently by Ziegler *et al.*²⁷ This chromophore absorbs at higher energy than the above cyanine dyes and it might be mentioned that concerns have been raised¹⁶ that the geminate recombination strategy might be less applicable for shorter wavelength emitters. Recent work²⁶ has shown that simple BOPHY derivatives undergo slow photochemical degradation in aerated solution, with the rate of bleaching being dependent on the solvent. The triplet-excited state is not involved in the bleaching chemistry. Now, the BOPHY dye has been equipped with one or two dibutylatedhydroxytoluene (BHT) residues. The latter is a lipophilic antioxidant used to minimize the effects of attack by free radicals.^{28,29} It can be used at low concentrations in food products, where it is considered to be a synthetic analogue of vitamin E. The new chromophore-quencher conjugates (CQC) were built by attaching BHT to BOPHY via an ethylene chain (Scheme 1). This maintains the two units in close proximity but the spacer does not promote mutual electronic communication or indeed orbital contact between the terminals.

Considerable interest has been shown of late in developing unusual organic transformations by way of photosensitized catalysis.^{30,31} One such photosystem³² has used an organic sensitizer in conjunction with a BHT derivative to generate good yields for amidation of aromatic aldehydes by reaction with amines. Reaction relies on bimolecular interception of excited states and reactive intermediates. As such, it is interesting to establish if similar photoreactions can be initiated using the covalently-attached CQC and we have therefore examined the photo-driven oxidative amidation of 4-bromobenzaldehyde with pyrrolidine in solution. The reaction proceeds smoothly under white light illumination to give clean products in yields exceeding 75% conversion. The intermediate believed to be responsible for the photo-fading process provides the impetus for photocatalysis.

View Article Online

Results and Discussion

Journal Name

Synthesis and Characterisation

A two-step approach was used to synthesize the target CQC derivatives (Scheme 1), abbreviated hereafter as P1B and P2B. The starting material, tetramethyl-BOPHY (TMBOPHY, referred to throughout as the parent dye) was synthesized^{26,27} in good yield by acid catalyzed condensation of 3,5dimethylpyrrole-2-carboxaldehyde with hydrazine to form the Schiff base, which was further reacted with BF₃·(OEt)₂ in the presence of N,N-diisopropylethylamine (DIPEA), as described before.³³ It might be noted that a 3-fold reduction in the volume of the reaction filtrate in vacuo allowed isolation of the Schiff base ligand in higher yields (90% relative to 3,5dimethylpyrrole-2-carboxaldehyde) as compared to the literature procedure (i.e., 65%). Knoevenagel condensation of the parent dye with 3,5-di-tertiary-butyl-4-hydroxybenzaldehyde, using the method developed by Ziessel et al.,34 generated a mixture of mono- and bis-condensed products as indicated by TLC and mass spectrometry. After twice repeating the evaporation cycle, any additional reaction time led to increased amounts of sideproducts, while employing the piperidine / acetic acid method in acetonitrile failed to give any significant conversion. The mixture was not purified at this stage due to the limited stability of the products during the attempted purification procedure. This situation was exacerbated by their similar RF values. Instead, the crude mixture was hydrogenated directly with H₂ at 1 atm., employing 10% Pd/C as the catalyst. Chromatography on silica gel provided the desired mono- and di-substituted CQCs in reasonable global yield relative to the parent dye; P1B (31%) and P2B (14%).

The ¹H-NMR spectra recorded for P1B and P2B (see Supporting Information) show the presence of peaks considered characteristic of both BHT and BOPHY units. The integral of the tertiary-butyl groups (1.4 ppm), hydroxyl (5.1 ppm), aromatic phenyl protons (7 ppm), and the ethylene bridge (two triplets at 2.9 ppm and 3.1 ppm) is consistent, respectively, with one and two BHT subunits being attached to the BOPHY module. At the same time, the triplet splitting pattern found for protons assigned to the ethylene bridge confirm that the hydrogenation reaction was successful. A simple pattern of three singlets (at 6.2 ppm and 8 ppm, respectively, for protons in β - and *meso*-positions and at 2.3 ppm for the methyl protons) is found for the BOPHY core in the specific case of the symmetrical P2B molecule. In the case of P1B, the β protons are slightly split while the *meso-* and the methyl-protons are subjected to minor broadening. The [M-F]+ molecular ion pattern found in ASAP/APCI high-resolution mass spectra of P1B and P2B further corroborate the assigned structures (see Supporting Information for details).

Photophysical properties of the CQC

The presence of the appended BHT residue has only minor effects on the absorption, excitation and fluorescence spectral profiles of the BOPHY unit^{26,27} in either fluid solution or thin plastic films (Figure 1). There is no aggregation under these conditions. The absorption (λ_{ABS}) and fluorescence (λ_{FLU}) maxima are fairly insensitive to the nature of the solvent (Table



Figure 1. Absorption (black curve), excitation (open circles) and fluorescence (red curve) spectra recorded for P1B in dichloromethane solution (upper panel) and a thin (ca. 400 micron) PMMA film cast from toluene (lower panel).

1). Relative to the parent (i.e., TMBOPHY) compound, fluorescence from P1B is less pronounced, with the quantum yield (Φ_F) showing a general correlation with the polarity of the solvent as expressed in terms of the static dielectric constant (ε_s). This behaviour is mirrored by changes in the excited-singlet state lifetime (τ_s), which shortens with increasing polarity as illustrated by the data listed in Table 1. However, in certain polar solvents, such as acetonitrile, the time-resolved emission decay profiles could no longer be well explained³⁵ in terms of a singleexponential component. In these solvents, the quality of the fit is improved³⁶ on invoking dual-exponential kinetics (see Supporting Information; Table 1). The same situation arises for P2B, where fluorescence quenching is somewhat more pronounced (Table 1). Again, the time-resolved emission decay profiles are well represented by single-exponential fits³⁵ in nonpolar solvents but the fit becomes less satisfactory³⁶ in polar solvents. The need to resort to dual-exponential kinetics is far from unusual when working with flexibly-linked dyads and is usually interpreted in terms of several families of noninterconverting conformers.37,38 These distributions differ in their ability to effect intramolecular fluorescence quenching. One family gives rise to a short lifetime, presumably indicating close proximity of the reactants, while the second family is subject to much weaker quenching.

Comparable behaviour has been seen in many other cases and attributed to differences in the level of orbital contact between the reactants.³⁹⁻⁴¹ With a short saturated connecting chain, it is difficult for the BHT group to approach near the BOPHY core, a

ARTICLE

Table 1. Summary of the photophysical properties recorded for the target CQCs in a range of solvents.

	P1B					P2B				
Solvent	$\Phi_{\rm F}$	$\tau_S \setminus$	ns ^(a)	$\lambda_{ABS} \setminus nm$	$\lambda_{FLU} \backslash nm$	$\Phi_{\rm F}$	$\tau_S \setminus ns^{\ (a)}$		$\lambda_{ABS} \setminus nm$	$\lambda_{FLU} \backslash nm$
C ₆ H ₁₂	0.75	2.8		472	489	0.73	2	.7	475	493
CH ₂ Cl ₂	0.74	2.8		470	490	0.71	2.7		471	493
BuCN ^(b)	0.44	1	.9	465	487	0.35	1	.9	468	491
BzCN ^(c)	0.67	1	.9	472	495	0.65	2.6		475	497
PC ^(d)	0.30	0.5	1.3 78%	464	486	0.23	0.6	1.2 73%	466	491
Acetone	0.32	0.9	1.7	464	487	0.23	0.4	1.4	466	490
		42%	58%				28%	72%		
CH ₃ CN	0.25	0.5	1.5	461	485	0.17	0.4	1.1	463	489
		71%	29%				63%	37%		
DMF ^(e)	0.17	0.5	2.5	466	490	0.06	0.3	1.6	468	494
		89%	11%				92%	8%		
CH ₃ OH	0.15	0.4	2.2	464	487	0.08	0.3	2.5	467	490
		89%	11%				96%	4%		
DMSO ^(f)	0.13	0.4	3.0	466	491	0.08	0.3	2.7	468	494
		89%	11%				94%	6%		

View Article Online DOI: 10.1039/C8PP00162F

(a) Singlet excited state lifetime derived by fitting the time-resolved emission decay profiles to either mono- or dual-exponential processes. In the latter case, the fractional amplitudes of the two lifetimes are given below the numerical value. (b) Butyronitrile. (c) Benzonitrile. (d) Propylene carbonate. (e) N,N-Dimethylformamide. (f) Dimethylsulfoxide.

situation well known from exciplex emission studies with other dyads.^{42,43} It is also possible that hydrogen bonding between BHT and an appropriate solvents will affect the conformational distributions. Many factors related to the solvent (e.g., size, structure, polarity, functional groups, viscosity) combine to mask any simple correlation between the extent of fluorescence quenching and the nature of the solvent (Table 1).

We can explain the overall fluorescence quenching in terms of light-induced electron transfer between BOPHY and BHT. Indeed, cyclic voltammetry carried out in CH₂Cl₂ indicates that one-electron reduction of the BOPHY unit occurs with a half-wave potential of -1.49 V vs Ag/Ag⁺ for both P1B and P2B.⁴⁴ This reduction process is not fully reversible and at slow scan rates (i.e., 100 mV/s) about 10% of the CQC (initial concentration 2 mM) is lost on each cycle. One-electron oxidation of the BOPHY unit can be recognized⁴⁴ with half-wave potentials of 1.32 and 1.28 V vs Ag/Ag⁺, respectively, for P1B

and P2B. These values are in accord with the limited literature data available for simpler BOPHY derivatives.^{44,45}

The cyclic voltammograms indicate a two-electron oxidation wave for each BHT unit at peak potentials lower than found for oxidation of BOPHY. Thus, P1B shows an irreversible, twoelectron wave with a peak at 1.27 V vs Ag/Ag⁺ while P2B shows a four-electron wave peaking at 1.20 V vs Ag/Ag⁺. Even on fast scans (i.e., 5 V/s), these oxidation steps are electrochemically irreversible. Most likely, oxidation of the phenol is followed by rapid loss of the proton, as is known to occur for tyrosine⁴⁶ and related phenols.⁴⁷ The poor reversibility of these electrochemical steps precludes proper determination of thermodynamic driving forces for light-induced, intramolecular electron transfer occurring within the CQC. Nonetheless, the ordering of the potentials indicates electron transfer from BHT to the excitedsinglet state of BOPHY will be favoured in polar solvents.⁴⁸ Therefore, the solvent effect observed for Φ_F and τ_S can be

Journal Name

attributed, at least in the major part, to thermodynamic effects associated with intramolecular electron transfer.⁴⁹ The significance of this finding is that interaction between the two subunits has to be taken into account when considering the mechanism for any subsequent photo-fading of the chromophore. It might be noted that such solvent effects are not observed for the parent fluorophore.

These CQCs differ from the earlier prototypes^{18,21,24,25} in as much as protection is aimed at the singlet-excited state, rather than the meta-stable triplet state. Quenching involves lightinduced charge transfer and is followed by rapid charge recombination within the geminate radical ion pair¹⁶ to restore the ground state (Scheme 2). Transient absorption spectroscopy did not resolve the presence of long-lived intermediates, nor indeed any sign of the triplet-excited state, a situation consistent with the rate of charge recombination exceeding that of charge separation. The latter is limited by the modest thermodynamic driving force and, at least in some conformations, by poor orbital contact. This circumstance is often observed with flexibly-linked dyads.³⁸ It is notable that charge recombination does not lead to formation of the triplet-excited state (Scheme 2).¹⁶ Efficient charge recombination serves to deactivate the excited state and thereby provide protection against photo-fading. In order to establish the effectiveness of this mode of operation, kinetic studies were undertaken to monitor the rate of photo-bleaching of the CQC in fluid solution.



Scheme 2. Representation of the photo-processes that follow from excitation of the BOPHY chromophore in the new CQCs: FL = fluorescence, CS = charge separation to form a geminate ion pair (CTS), CR = charge recombination to restore the ground state. Intersystem crossing to the triplet manifold is not observed.

Photochemical bleaching in polar solvent

Solutions of P2B in air-equilibrated polar solvents were illuminated with broadband light to simulate exposure to sunlight. Bleaching of the absorption profile occurs but there is no obvious indication for formation of a coloured product. Increased absorption does appear in the near-UV region and, at early times, isosbestic points are seen at wavelengths around 370 nm. Two examples of this behaviour are shown as Figure 2 and further examples are given in the Supporting Information. Global analysis⁵⁰ of the spectral data accompanying loss of the chromophore, using the entire wavelength window from 400 nm to 480 nm, allows the reaction kinetics to be evaluated. Thus, the rate of bleaching (ω) at any wavelength was determined as a function of chromophore concentration. This rate, at any given



Figure 2. Progressive photo-bleaching observed for P2B in air-equilibrated (a) acetonitrile and (b) butyronitrile under broadband illumination. Absorption spectra were recorded at frequent intervals up to 100 hours continuous exposure.

time, depends on the total light intensity (I_0) and on the fraction of light absorbed by the chromophore (IABS). The latter term depends on the chromophore concentration as indicated by Equation 1.⁵¹ In polar solvents, notably acetonitrile, butyronitrile, acetone and DMF, it is found that the reaction rate is quite insensitive to the chromophore concentration, at least over most of the bleaching profile (Figure 3). This indicates that the reaction is essentially zero-order with respect to chromophore concentration but is linearly dependent on the number of photons absorbed. Under these conditions, the rate of bleaching is controlled entirely by the light flux (Equation 2). This allows estimation of a *pseudo*-zero-order rate constant (k₀), which is the rate constant under standardised incident light intensity (i.e., $I_0 = 1$), as illustrated by Figure 3. The derived k_0 values are collected in Table 2. It was observed that P1B followed similar behaviour but with somewhat slower rates of bleaching.

$$I_{ABS} = 1 - 10^{-\epsilon [P2B]}$$
 (1)

$$\omega = I_0 \times I_{ABS} \times k_0 \times [P2B]^0 \quad (2)$$

An important variation is found in benzonitrile solution where it will be recalled fluorescence quenching is less noticeable than for the other polar solvents. Here, the rate of photo-bleaching (ω) increases slightly at early times before reaching a plateau. On longer exposure times, the rate begins to decrease (Figure 4). As above, bleaching of the BOPHY chromophore does not lead to the appearance of a relatively stable product that absorbs in the visible region. The rate of bleaching is consistent across the entire 400-480 nm spectral window. The shape of the rate *vs* concentration plot exhibits the



Figure 3. Effect of chromophore concentration on the light-intensity corrected rate of photo-bleaching for P2B in air-equilibrated (a) acetonitrile and (b) butyronitrile. The horizontal lines drawn through the higher concentration data correspond to the averaged zero-order rate constants.



Figure 4. (a) Progressive photo-bleaching observed for P2B in air-equilibrated benzonitrile under broadband illumination. (b) Kinetic fit to the autocatalytic expression given as Equation 3 with the parameters mentioned in the text. The inset shows how the light-intensity corrected rate of bleaching depends on P2B concentration in an analogous manner to that illustrated in Figure 3.

general appearance of that expected^{52,53} for an autocatalytic process. Indeed, the reaction kinetics, again treated in terms of global analysis across the 400-480 nm window, fit nicely to Equation 3.⁵⁴ Here, $k_1 (= 0.070 \text{ h}^{-1})$ is a first-order rate constant attributed to a chemical reaction that forms an autocatalytic species and k_{AC} (= 0.0084 μ M⁻¹ h⁻¹) is the corresponding bimolecular rate constant for autocatalysis (Table 2). At high conversion, the rate of reaction decreases due to the scarcity of substrate and the linear fit to Equation 3 becomes lost.

$$\frac{\omega}{[P2B]} = (k_1 + k_{AC} [P2B]_0) - k_{AC} [P2B]$$
(3)

There is a general trend for the derived rate constant, k_0 , attributed to the photo-bleaching step to increase with decreasing

Table 2. Summary of the derived rate constants for the photo-bleaching of Paralle various air-equilibrated solvents. DOI: 10.1039/C8PP00162F

8s	Φ_{F}	Rate constant
2	0.73	
26	0.65	1.5 ^(d, e)
20.7	0.35	0.78 ^(d)
20.7	0.20	0.75 ^(d)
37.5	0.17	0.60 ^(d)
36.7	0.06	0.60 ^(d)
	εs 2 26 20.7 20.7 37.5 36.7	εs Φ _F 2 0.73 26 0.65 20.7 0.35 20.7 0.20 37.5 0.17 36.7 0.06

(a) Benzonitrile. (b) Butyronitrile. (c) N,N-Dimethylformamide. (d) Refers to the *pseudo*-zero-order rate constant having units of μ M h⁻¹ (see inset to Figure 4). (e) Fit is improved using the autocatalysis expression given as Equation 3.



Scheme 3. Representation of the processes that follow from excitation of the BOPHY chromophore in the new CQCs: FL = fluorescence, CS = charge separation to form a geminate ion pair (CTS), CR = charge recombination, BL = bleaching, SH = self-healing. The notation B-BHT~ is used to indicate the "stable" product that promotes further bleaching of the chromophore, later identified as being the hydroperoxide.

solvent polarity (Table 2), although the variation is modest. Moreover, a clear correlation exists between the fluorescence quantum yield and k₀ in polar solvents. When considered in terms of the solvent dielectric constant (ε_s), benzonitrile gives an anomalously high fluorescence quantum yield and a surprisingly high rate of photo-fading. This can be explained in terms of π stacking between the chromophore and the phenyl ring of the solvent as was observed previously by NMR spectroscopy with toluene and the parent BOPHY.²⁶ This transient alignment of solvent and chromophore would force the appended BHT residue away from the chromophore. The resultant "open" conformation is less amenable to light-induced electron transfer because of the increased separation. Hence, intramolecular charge transfer is switched off and the consequent protection is lost. Indeed, the Φ_F found for benzonitrile approaches that observed in cyclohexane solution.

We interpret this overall behaviour in terms of Scheme 3, where excitation of the BOPHY chromophore leads to transient population of a radical ion pair due to light-induced charge transfer from BHT to BOPHY.⁵⁵ Rapid geminate recombination restores the ground state but, according to the cyclic voltammetry results, a minor fraction of the oxidized BHT fragment undergoes irreversible chemical transformation. Most likely, this reaction is initiated by loss of the phenoxyl proton from the BHT π -radical cation.⁵⁶ It is this deprotonation that breaks the recycling step and leads to formation of an oxy-radical.⁵⁷ The corresponding BOPHY π -radical anion is rapidly re-oxidized by

Journal Name

ARTICLE



Figure 5. Formation of P1B-OOH and associated changes in the 1H-NMR spectrum of P1B in acetone-d₆ after illumination with white light. *Peak intensities in the 1–1.5 ppm region are decreased by a factor of 5-fold for a clearer image.

molecular oxygen (*vide infra*). The fate of the oxy-radical, which leads to formation of one or more products that promote further bleaching of BOPHY, was explored by NMR spectroscopy (*vide infra*). In this proposed scheme, escape from the geminate ionpair plays a key role in the overall process. This is evident from the link between Φ_F and k_0 and is confirmed by the situation outlined for benzonitrile. Increasing the oxygen concentration has no real effect on the reaction kinetics. In the absence of oxygen, bleaching occurs slowly but by a different mechanism.

The course of reaction for P1B in acetone-d₆ was followed by ¹H-NMR spectroscopy (Figure 5). Illumination causes clean conversion to an intermediate species within a few hours. It is clear that most of the chemistry is associated with the BHT residue. Thus, the proton from the hydroxyl group (a) is shifted downfield by about 5 ppm to what looks like a hydroperoxide peak ($\delta = 10.9$ ppm).⁵⁸ At the same time, protons from phenyl (b), ethylene bridge (c) and *tertiary*-butyl moieties (d) show shifts on the order of 0.15 to 0.8 ppm. This is in agreement with the formation of a 4-hydroperoxycyclohexa-2,5-dien-1-one ring due to reaction of the BHT radical and the hydroperoxyl radical (Figure 5). Additional proof is provided by the peak at m/z = 611found in high-resolution *nano*-ESI mass spectrometry, that matches well with the $[M+Na]^+$ molecular ion pattern (see Supporting Information). Conversion to the hydroperoxyl P1B-OOH is quite selective, reaching 90% yield at modest conversion of starting compound. This falls to 70% at full consumption, possibly reflecting the high reactivity of the resultant P1B-OOH species. These NMR studies indicate that little damage occurs at the BOPHY site during the initial phase but continued illumination leads to the formation of multiple products, as is evidenced by the appearance of many new peaks and broadening of the entire spectrum.

The quantum yield for the overall bleaching process is kept low by the high level of reversibility of the initial charge-transfer

Published on 25 April 2018. Downloaded by University of New England on 30/04/2018 17:32:25

Journal Name



Scheme 4. Representation of the effect of added DABCO (DAB) on the photoprocesses that follow from excitation of the BOPHY chromophore in the new CQCs.

process. Short illumination of P2B in aerated acetonitrile solution at 390 nm allows estimation of the quantum yield for the bleaching of the BOPHY chromophore as being on the order of 10^{-7} . Laser flash photolysis of P1B, with excitation at 355 nm, confirms the high level of reversibility of the primary photochemical step. Under such conditions, most of the signal corresponding to ground-state absorption by the BOPHY chromophore recovers within the excitation pulse. A small fraction recovers on a much slower timescale with a half-life of ca. 300 ns in air-equilibrated acetonitrile. This latter process is attributed to re-oxidation of the BOPHY π -radical anion by molecular oxygen. The activation energy measured for the overall bleaching in air-equilibrated DMF was found to be 9.2 kJ/mol, which is comparable to the temperature dependence for the viscosity of this solvent.⁵⁹

A number of trapping studies were attempted. Thus, the typical quenchers DMPO (a spin trap⁶⁰ that reacts with O-centred radicals) and DABCO (which, among other reactions, is a quencher^{61,62} for singlet oxygen) were added at 1 mM concentration to solutions of P2B in acetonitrile. Addition of DABCO was seen to exacerbate the bleaching while DMPO had an initial inhibiting effect on the rate of photo-fading but later catalysed loss of the chromophore. It is considered that DMPO intercepts the initially formed phenoxyl radical but this beneficial effect is soon lost as reactive products emerge. It was also found that DABCO caused dynamic fluorescence quenching due to light-induced electron transfer.⁶³ Transient absorption spectroscopy was used to show that, at high concentrations (i.e., 0.1 M) of DABCO, the intramolecular electron transfer is replaced by an intermolecular reaction (Scheme 4). Now the radical ion products recombine rapidly within the geminate ion pair without separation.^{14,16,18,64} This latter reaction provides stabilisation against photo-fading but is far from being practical because of the high concentrations needed.

Photo-bleaching in nonpolar solvents

Due to thermodynamic restrictions,⁶⁵ it is unlikely that lightinduced intramolecular electron transfer will be effective in nonpolar media. Nonetheless, photo-bleaching occurs quickly under these conditions (Figure 6), again without formation of coloured products. There is, however, a partial accumulation of products absorbing in the near-UV region. Global analysis of the kinetic data acquired over the 420-490 nm window indicates that the bleaching chemistry might be more complex than found in polar solvents. For both CQCs in air-equilibrated vertexane, illumination with broadband light induces a relatively fast reaction that causes only a minor change in the absorption spectral profile. The absorption data, corrected for minor changes in the fraction of light absorbed by the chromophore,⁶⁶ fits well to first-order kinetics over the early stage of reaction. The corresponding first-order rate constants (k1) are 0.015 and 0.008 h⁻¹, respectively, for P1B and P2B. It is noticeable that this initial phase of the reaction persists far longer for P2B than for P1B. The implication is that the BHT residue is involved in the process. Following this initial reaction, the rate of photobleaching increases to a maximum before decreasing as the course of reaction continues (Figure 7). The parabolic form of the rate vs conversion profile is as might be expected⁵²⁻⁵⁴ for an autocatalytic process, as already noted for benzonitrile solutions.



Figure 6. Progressive photo-bleaching observed for (a) P1B and (b) P2B in airequilibrated cyclohexane under broadband illumination. Absorption spectra were recorded at frequent intervals up to 105 hours continuous exposure.

It is apparent from examination of Figure 6 that the bleaching process is far from complete. Indeed, the rate of photo-bleaching, ω , reaches an optimum value before decreasing with increasing reaction time but not ceasing altogether. The extent of bleaching is significantly more pronounced for P2B than for P1B, again fully consistent with the idea that the BHT residue is involved. It appears that the bleaching chemistry enters the dormant phase at precise conversion fractions. For P1B, this corresponds to *ca*. 50% conversion to the bleached form while the conversion fraction is *ca*. 75% for P2B. Such behaviour must be indicative of the bleaching mechanism and allows definition of the reaction stoichiometry as follows:

In cyclohexane solution, illumination of P1B leads to the relatively fast conversion to a product whereby the BHT residue has been chemically modified. It is tempting to raise the likelihood that this involves formation of the hydroperoxide but we do not have experimental support for this claim. The modified form is designated as B-BHT• on Scheme 5, where B is used to

Journal Name

designate BOPHY. It has an absorption profile similar to that of the starting chromophore. Two B-BHT[•] residues react together to bleach one of the chromophores and to render the second chromophore intact but with the BHT residue deactivated (designated as B-X on Scheme 5). For P2B under the same conditions, illumination leads to successive modification of the two BHT residues followed by similar chemistry to that outlined for P1B (Scheme 5). The net result is that this type of photobleaching will account for 50% of P1B but 75% of P2B. A key feature of this scheme is that B-BHT[•] does not attack the chromophore directly but bleaching occurs only after diffusional approach of two B-BHT[•] residues.



Figure 7. Evolution of the reaction rate as a function of the degree of bleaching for P1B (filled circles) and P2B (open circles) in air-equilibrated cyclohexane under broadband illumination.

	B-BHT hv B-BHT•
	$2B-BHT^{\bullet} \longrightarrow B-X + B'-X$ (inactive) (bleached)
В	HT-B-BHT → •BHT-B-BHT
2BF	IT-B-BHT [●] → X-B-BHT + X-B'-BHT (active) (bleached)
	X-B-BHT → X-B-BHT•
2	X-B-BHT [•] → X-B-X + X-B'-X (inactive) (bleached)

Scheme 5. Outline of the reactions proposed to account for the bleaching stoichiometry observed for P1B and P2B in cyclohexane solution. The symbol B' is intended to describe a bleached chromophore where X refers to a damaged BHT residue that cannot recycle.

Figure 7 shows how the rate of bleaching evolves as a function of the extent of bleaching (i.e., the loss of colour). The reaction corresponds to the simple scheme given as an inset to the Figure. The first-order process, which leads to only a small degree of bleaching, occurs with a rate constant of k_1 , as described above. In principle, the full reaction profile can be evaluated to obtain an estimate for the second-order rate constant but this is not straightforward and requires specialised kinetics treatments,⁶⁷ especially for P2B. The idea that a substantial



fraction of the CQC is recycled in a form that lacks, a reactive

Figure 8. Absorption spectra recorded during the course of photo-bleaching of (a) P1B and (b) P2B dispersed in a thin film of PMMA. The illumination source was light white and the films were cast from toluene. Spectra were recorded at regular intervals up to 60 hours.

Photo-bleaching in thin plastic films

To further assess the significance of the bimolecular bleaching step identified above, samples of the CQCs were prepared after incorporation into thin (ca. 400 micron) PMMA films prepared by casting from toluene. The dielectric constant⁶⁸ of these films is similar to that of cyclohexane although the concentration of dissolved oxygen and the diffusion coefficients of the solutes are likely to differ markedly from those for fluid solution. Under illumination, the plastic-bound CQCs bleach as in solution (Figure 8). Again, the entire spectral envelope fades under exposure to white light and there is no clear indication for the transient formation of a coloured intermediate. Global analysis of the bleaching data indicates that loss of chromophore is well described in the form of two successive first-order reactions (Figure 9). The faster step accounts for about 12% of the chromophore and occurs with half-lives of 2.0 h and 2.6 h, respectively, for P1B and P2B. The slower step takes place with half-lives of 160 h and 270 h, respectively. These reaction halflives are corrected for the number of photons absorbed but it might not be wise to make a direct comparison of the derived values with those from solution. The important point, however, is that the bimolecular process is inhibited in the film and replaced by a slow unimolecular step.

Photocatalytic amidation

Organic hydroperoxides⁶⁹ can be considered as relatively strong oxidants useful for driving certain organic transformations.⁷⁰ With this in mind, we examined the possibility to trap the *in situ* formed BHT-OOH species in order to promote amide synthesis³² between an aldehyde and an amine through oxidation of the intermediate α -hydroxyamine. The amide functional group plays



Figure 9. Kinetic profiles recorded for photo-bleaching of the CQC in a thin PMMA film where diffusion is severely limited. The solid lines drawn through the data points correspond to fits to two successive first-order reactions, with the parameters given in the text.

a critical role in both organic and, more importantly, bioorganic chemistry and it is recognised⁷¹⁻⁷⁴ that direct amidation of aldehydes avoids the additional oxidative step. Thus, when the above photo-bleaching reaction is carried out in the presence of 4-bromobenzaldehyde (30 mM), pyrrolidine (90 mM) and 1 mol% P2B, formation of (4-bromophenyl) (pyrrolidin-1-yl)methanone takes place (Scheme 6). Performing the reaction in acetonitrile gives only 5% conversion before P2B is completely bleached. Changing the solvent to the less polar dioxane increases the yield to over 49% relative to the starting aldehyde.

Excess pyrrolidine leads to faster bleaching of the photocatalyst and thus lower overall reaction yields for amide synthesis. Absorption and fluorescence spectroscopy indicates that it is depletion of the photocatalyst that causes the reaction to stop prematurely. Consequently, increasing the amount of photocatalyst to 2 mol% leads to complete consumption of the starting material within 24 h and with a selectivity of 75% for the formation of (4-bromophenyl)(pyrrolidin-1-yl)methanone as determined by ¹H- and ¹³C-NMR spectroscopy.²⁹ These reaction conditions are mild and require no metal catalyst or hazardous reagent.



Scheme 6. Outline of the oxidative amidation of 4-bromobenzaldehyde with pyrrolidine promoted by illumination of P2B.

Conclusion

Published on 25 April 2018. Downloaded by University of New England on 30/04/2018 17:32:25

There is tremendous current interest in the development of strategies that aid protection of organic chromophores against light-induced degradation. This research is driven by the ever-expanding range of applications being proposed for fluorescent dyes and by the emerging fields of single-molecule microscopy and super-resolution imaging microscopy. Of the promising approaches being advocated, we draw attention to two systems that have been shown to bring about major improvements in photoprotection; namely, the rapid charge-recombination (with or without spin conversion) in geminate radical ion pairs¹⁴⁻¹⁶ and

the covalent attachment of a stabilizer to the chromophore 18-23 We have designed a pair of new chromophore-quencher conjugates that combine key features of the two approaches. Thus, illumination of a BOPHY-BHT conjugate, where BHT refers to a butylated hydroxytoluene anti-oxidant, in polar solution causes light-induced, intramolecular charge transfer. The resultant radical ion pair is prone to rapid charge recombination, in line with many other such systems,^{75,76} but loss of a proton from the phenolic π -radical cation^{46,47} provides an escape route. This deprotonation, which has been recognized for certain acridinium-based dyads,⁷⁷ initiates the photo-bleaching process and, in aerated solution, leads to formation of an organic hydroperoxide that readily enters into subsequent chemical reactions at ambient temperature. Without a suitable substrate, the hydroperoxide promotes bleaching of the chromophore. It is, therefore, a key intermediate in the cycle and, used properly, offers an opportunity to eliminate the sensitizer once any useful work is complete. We have demonstrated its utility by driving an amidation reaction under exceptionally mild conditions but other oxidative syntheses might be possible with the same approach.

The reaction kinetics depend on the nature of the local environment, possibly reflecting different levels of reactivity of key intermediates. Perhaps the most interesting case from a mechanistic viewpoint involves nonpolar solutions. Here, the net stoichiometry clearly indicates that the primary intermediate formed in a photochemical step undergoes reaction with a second such species. This reaction destroys one of the chromophores but converts the second chromophore to a form that has greatly enhanced photostability. This represents a new type of selfhealing.²¹ Equally important is the effect of a flat aromatic solvent, namely benzonitrile, which curtails the initial electron transfer reactions and thereby promotes autocatalysis.

This work serves to indicate how a damaging reaction, namely the photodegradation of a chromophore, can be put to good use by, for example, the synthesis of a valuable reagent under mild conditions.^{30,31} Other applications might be imagined for the hydroperoxide intermediate. For example, we have shown that the CQCs function as photo-initiators for polymerization⁷⁸ of methyl methacrylate at room temperature to leave a colorless plastic (see Supporting Information). Under visible light, P2B is well able to bleach other dyes (notably Chlorophenol Red), offering possibilities to design photosystems for antimicrobial disinfectation⁷⁹ and/or removal of toxic wastes.⁸⁰ Work is underway to test the capacity of these CQCs for the sustainable epoxidation^{81,82} of alkenes under green conditions. There are no conflicts to declare.

Acknowledgements

We thank EPSRC for the award of an Industrial CASE award (OJW) and Newcastle University for financial support of this work. We also thank the EPSRC Mass Spectrometry service at Swansea for access to facilities.

References

Journal Name

- 1 M. C. De Rosa and R. J. Crutchley, Photosensitized singlet oxygen and its applications, *Coord. Chem. Rev.*, 2002, **233**, 351-371.
- 2 A. A. Gorman and M. A. J. Rodgers, Singlet molecular-oxygen, *Chem. Soc. Rev.*, 1981, **10**, 205-231.
- 3 P. R. Ogilby and C. S. Foote, Chemistry of singlet oxygen. 42. Effect of solvent, solvent isotopic-substitution, and temperature on the lifetime of singlet molecular-oxygen (1delta-g), J. Am. Chem. Soc., 1983, **105**, 3423-3430.
- 4 M. A. H. Alamiry, A. Harriman, A. Haefele and R. Ziessel, Photochemical bleaching of an elaborate artificial lightharvesting antenna, *ChemPhysChem*, 2015, **16**, 1867-1872.
- 5 A. Telfer, Too much light? How beta-carotene protects the photosystem II reaction centre, *Photochem. Photobiol. Sci.*, 2005, **4**, 950-956.
- 6 R. Edge, D. J. McGarvey and T. G. Truscott, The carotenoids as anti-oxidants a review, *J. Photochem. Photobiol. B Biol.*, 1997, **41**, 189-200.
- 7 H. Zöllinger, Color Chemistry. Syntheses, Properties and Applications of Organic Dyes and Pigments. VHCA Publishers; Zurich. 3rd Edition, Revised. 2003.
- 8 N. K. Bridge and G. Porter, Primary photoprocesses in quinones and dyes. Part 1. Spectroscopic detection of intermediates, *Proc. Roy. Soc. A*, 1958, **244**, 259-275.
- 9 D. K. Palit, H. Pal, T. Mukherjee and J. P. Mittal, Triplet excitedstates and semiquinone radicals of 1,4-disubstituted anthraquinones, *J. Photochem. Photobiol. A Chem.*, 1990, **52**, 375-390.
- 10 B. Armitage, C. J. Yu, C. Devadoss and G. B. Schuster, Cationic anthraquinone derivatives as catalytic DNA photonucleases mechanisms for DNA-damage and quinone recycling, *J. Am. Chem. Soc.*, 1994, **116**, 9847-9859.
- 11 J. L. Alejo, S. C. Blanchard and O. S. Andersen, Small-molecule photostabilizing agents are modifiers of lipid bilayer properties, *Biophys. J.*, 2013, **104**, 2410-2418.
- 12 S. van der Linde, S. Wolter, M. Heilemann and M. Sauer, The effect of photoswitching kinetics and labelling densities on super-resolution fluorescence imaging, J. *Biotechnol.*, 2010, 149, 260-266.
- 13 M. Levitus and S. Ranjit, Cyanine dyes in biophysical research: The photophysics of polymethine fluorescent dyes in biomolecular environments, *Quart. Rev. Biophys.*, 2011, **44**, 123-151.
- 14 V. Glembockyte and G. Cosa, Redox-based photostabilizing agents in fluorescence imaging: The hidden role of intersystem crossing in geminate radical ion pairs, *J. Am. Chem. Soc.*, 2017, **139**, 13227-13233.
- 15 C. F. Calver, B. A. Lago, K. S. Schanze and G. Cosa, Enhancing the photostability of poly(phenylene ethynylene) for single particle studies, *Photochem. Photobiol. Sci.*, 2017, **16**, 1821-1831.
- 16 P. Holzmeister, A. Gietl and P. Tinnefeld, Geminate recombination as a photoprotection mechanism for fluorescent dyes, *Angew. Chem., Int. Ed.*, 2014, **53**, 5685-5688.
- 17 J. Vogelsang, C. Steinhauser, C. Forthmann, I. H. Stein, B. Person-Skegro, T. Cordes and P. Tinnefeld, Make them blink: Probes for super-resolution microscopy, *ChemPhysChem*, 2010, **11**, 2475-2490.
- R. B. Altman, Q. Zheng, Z. Zhou, D. S. Terry, J. D. Warren and S. C. Blanchard, Enhanced photostability of cyanine fluorophores across the visible spectrum, *Nature Methods*, 2012, **9**, 68.
- 19 Q. Zheng, S. Jockusch, Z. Zhou and S. C. Blanchard, The contribution of reactive oxygen species to the photobleaching of organic fluorophores, *Photochem. Photobiol.*, 2014, **90**, 448-454.

- 20 Q. Zheng, M. F. Juette, S. Jockusch, M. R. Wasserman, Z. Zhou, R. B. Altman and S. C. Blanchard, Dultra stable porgatic fluorophores for single-molecule research, *Chem. Soc. Rev.*, 2014, **43**, 1044-1056.
- 21 J. H. M. van der Velde, J. Oelerich, J. Y. Huang, J. H. Smit. M. Hiermaier, E. Ploetz, A. Herrmann, G. Roelfes and T. Cordes, The power of two: Covalent coupling of photostabilizers for fluorescence applications, *J. Phys. Chem. Lett.*, 2014, **5**, 3792-3798.
- 22 J. H. M. Van der Velde, J. Oelerich, J. Y. Huang, J. Smits, A. A. Jazi, K. Galiani, K. Kolmakov, S. Guoridis, C. Eggeling, A. Hermann, G. Roelfes, and T. Cordes, A simple and versatile design concept for fluorophore derivatives with intramolecular photostabilization, *Nature Commun.*, 2016, 7, 10144.
- 23 Q. Zheng, S. Jockusch, G. G. Rodriguez-Calero, Z. Zhou, H. Zhao, R. B. Altman, H. D. Abruñab and S. C. Blanchard, Intramolecular triplet energy transfer is a general approach to improve organic fluorophore photostability, *Photochem. Photosbiol. Sci.*, 2016, **15**, 196-203.
- 24 P. Tinnefeld and T. Cordes, 'Self-healing' dyes: Intramolecular stabilization of organic fluorophores, *Nature Methods*, 2012, 9, 426-427.
- 25 Q. Zheng, S. Jockusch, Z. Zhou, R. B. Altman, J. D. Warren, N. J. Turro and S. C. Blanchard, On the mechanisms of cyanine fluorophore photostabilization, *J. Phys. Chem. Lett.*, 2012, 3, 2200-2203.
- 26 O. Woodford, A. Harriman, W. McFarlane and C. Wills, Dramatic effect of solvent on the rate of photobleaching of organic pyrrole-BF₂ (BOPHY) dyes, *ChemPhotoChem*, 2017, 1, 317-325.
- 27 I. S. Tamgho, A. Hasheminasab, J. T. Engle, V. N. Nemykin and C. J. Ziegler, A new highly fluorescent and symmetric pyrrole-BF₂ chromophore: BOPHY, *J. Am. Chem. Soc.*, 2014, **136**, 5623-5626.
- 28 O. Brede, H. Orthner, V. Zubarev and R. Hermann, Radical cations of sterically hindered phenols as intermediates in radiation-induced electron transfer processes, *J. Phys. Chem.*, 1996, **100**, 7097-7105.
- 29 M. Foti, K. U. Ingold and J. Lusztyk, The surprisingly high reactivity of phenoxyl radicals, *J. Am. Chem. Soc.*, 1994, **116**, 9440-9447.
- 30 E. R. Welin, C. Le, D. M. Arias-Rotondo, J. K. McCusker and D. W. C. MacMillan, Photosensitized, energy transfer-mediated organometallic catalysis through electronically excited nickel(II), *Science*, 2017, **355**, 380-385.
- 31 M. Parasram and V. Gevorgyan, Visible light-induced transition metal-catalyzed transformations: Beyond conventional photosensitizers, *Chem. Soc. Rev.*, 2017, 46, 6227-6240.
- 32 X.-F. Wang, S.-S. Yu, C. Wang, D. Xue and J. B. Xiao, BODIPY catalyzed amide synthesis promoted by BHT and air under visible light, *Org. Biomol. Chem.*, 2016, **14**, 7028-7037.
- 33 A. Mirloup, Q. Huaulmé, N. Leclerc, P. Lévêque, T. Heiser, P. Retailleau and R. Ziessel, Thienyl-BOPHY dyes as promising templates for bulk heterojunction solar cells, *Chem. Commun.*, 2015, **51**, 14742-14745.
- 34 R. Ziessel, T. Bura and J.-H. Olivier, Elaborating boron dipyrromethene dyes with conjugated polyaromatic frameworks, *Synlett*, 2010, **15**, 2304-2310.
- 35 D. V. O'Connor and D. Phillips, Time-Correlated Single Photon Counting, Academic Press, London, 1984.
- 36 H. E. Grecco, P. Roda-Navarro and P. J. Verveer, Global analysis of time correlated single photon counting FRET-FLIM data, *Opt. Express*, 2009, **17**, 6493-6508.
- 37 W. Schroeyers, R. Vallee, D. Patra, J. Hofkens, S. Habuchi, T. Vosch, M. Cotlet, K. Mullen, J. Enderlein and F. C. De Schryver, Fluorescence lifetimes and emission patterns probe the 3D

orientation of the emitting chromophore in a multichromophoric system, *J. Am. Chem. Soc.*, 2004, **126**, 14310-14311.

- 38 A. Harriman, K. J. Elliott, M. A. H. Alamiry, L. Le Pleux, M. Severac, Y. Pellegrin, E. Blart, C. Fosse, C. Cannizzo, C. R. Mayer and F. Odobel, Intramolecular electron transfer reactions observed for Dawson-type polyoxometalates covalently linked to porphyrin residues, *J. Phys. Chem. C*, 2009, **113**, 5834-5842.
- 39 F. D. Lewis, J. M. Wagner-Brennan and J. M. Denari, Intramolecular electron transfer in donor-spacer-acceptor systems with alkylamide spacers, *J. Phys. Chem. A*, 1998, **102**, 519-525.
- 40 A. F. Morales, G. Accorsi, N. Armaroli, F. Barigelletti, S. J. A. Pope and M. D. Ward, Interplay of light antenna and excitation "energy reservoir" effects in a bichromophoric system based on ruthenium-polypyridine and pyrene units linked by a long and flexible poly(ethylene glycol) chain, *Inorg. Chem.*, 2002, **41**, 6711-6719.
- 41 S. Mula, K. J. Elliott, A. Harriman and R. Ziessel, Energy transfer by way of an exciplex intermediate in flexible boron dipyrromethene-based allosteric architectures, *J. Phys. Chem. A*, 2010, **114**, 10515-10522.
- 42 A. Onkelinx, F. C. De Schryver, L. Viaene, M. Van der Auweraer, K. Iwai, M. Yamamoto, M. Ichikawa, H. Masuhara, M. Maus and W. Rettig, Radiative depopulation of the excited intramolecular charge-transfer state of 9-(4-(N,Ndimethylamino)phenyl)phenanthrene, J. Am. Chem. Soc., 1996, **118**, 2892-2902.
- 43 Y. V. Il'ichev, W. Kuhnle and K. A. Zachariasse, Intramolecular charge transfer in dual fluorescent 4-(dialkylamino)benzonitriles. Reaction efficiency enhancement by increasing the size of the amino and benzonitrile subunits by alkyl substituents, J. Phys. Chem. A, 1998, **102**, 5670-5680.
- 44 Q. Huaulmé, A. Mirloup, P. Retailleau and R. Ziessel, Synthesis of highly functionalized BOPHY chromophores displaying large Stokes shifts, *Org. Lett.*, 2015, **17**, 2246-2249.
- 45 Y. V. Zatsikha, D. B. Nemez, R. L. Davis, S. Singh, D. E. Herbert, A. J. King, C. J. Ziegler and V. N. Nemykin, Testing the limits of the BOPHY platform: Preparation, characterization, and theoretical modeling of BOPHYs and organometallic BOPHYs with electron-withdrawing groups at beta-pyrrolic and bridging positions, *Chem. Eur. J.*, 2017, **23**, 14786-14796.
- 46 A. Harriman, Further comments on the redox potentials of tryptophan and tyrosine, J. Phys. Chem., 1987, **91**, 6102-6104.
- 47 J. Bonin, C. Costentin, C. Louault, M. Robert, M. Routier and J. M. Saveant. Intrinsic reactivity and driving force dependence in concerted proton-electron transfers to water illustrated by phenol oxidation, *Proc. Natl. Acad. Sci. USA*, 2010, **107**, 3367-3372.
- 48 H. Oevering, M. N. Paddon-Row, M. Heppener, A. M. Oliver, E. Cotsaris, J. W. Verhoeven and N. S. Hush, Long-range photoinduced through-bond electron-transfer and radiative recombination via rigid nonconjugated bridges – distance and solvent dependence, J. Am. Chem. Soc., 1987, 109, 3258-3269.
- 49 A. Harriman, G. Porter and N. Searle, Reversible photooxidation of zinc tetraphenylporphyrin by benzo-1,4quinone, J. Chem. Soc., Faraday Trans. II, 1979, 75, 1515-1521.
- 50 P. Kuzmič, Program DYNAFIT for the analysis of enzyme kinetic data: Application to HIV proteinas, *Anal. Biochem.*, 1996, **237**, 260-273.
- 51 J. K. G. Karlsson, O. J. Woodford, R. Al-Aqar and A. Harriman, Effects of temperature and concentration on the rate of photobleaching of Erythrosine in water. *J. Phys. Chem. A*, 2017, **121**, 8569-8576.
- 52 F. Mata-Perez and J. F. Perez-Benito, The kinetic rate law for autocatalytic reactions, J. Chem. Educ., 1987, 64, 925-927.

- 53 J. F. Perez-Benito, C. Arais and E. Amat, A kinetic study of the reduction of colloidal manganese dioxide 19x0934167 Acide 24: Colloid. Interface Sci., 1996, 177, 288-297.
- 54 A. K. Horvath, I. Nagypal and I. R. Epstein, Three autocatalysts and self-inhibition in a single reaction: A detailed mechanism of the chlorite-tetrathionate reaction, *Inorg. Chem.*, 2006, **45**, 9877-9883.
- 55 D. M. Guldi, Fullerene-porphyrin architectures; photosynthetic antenna and reaction center models, *Chem. Soc. Rev.*, 2002, **31**, 22-36.
- 56 C. Costentin, M. Robert and J.-M. Saveant, Concerted protonelectron transfers in the oxidation of phenols, *Phys. Chem. Chem. Phys.*, 2010, **12**, 11179-11190.
- 57 W. H. Koppenol, D. M. Stanbury and P. L. Bounds, Electrode potentials of partially reduced oxygen species, from dioxygen to water, *Free Rad. Biol. Med.*, 2010, **49**, 317-322.
- 58 N. A. Stephenson and A. T. Bell, Quantitative analysis of hydrogen peroxide by H-1 NMR spectroscopy, *Anal. Bioanal. Chem.*, 2005, **381**, 1289-1293.
- 59 Viscosity of Pure Organic Liquids and Binary Liquid Mixtures. Supplement to IV/18. Lechner, M. D. Editor: Landolt-Börnstein – Group IV Physical Chemistry, Vol. 25, 2009.
- 60 I. Yamazaki and L. H. Piette, EPR spin-trapping study on the oxidizing species formed in the reaction of the ferrous ion with hydrogen-peroxide, *J. Am. Chem. Soc.*, 1991, **113**, 7588-7593.
- 61 E. Baciocchi, T. Del Giacco, F. Elisei, M. F. Gerini, M. Guerra, A. Lapi and P. Liberali, Electron transfer and singlet oxygen mechanisms in the photooxygenation of dibutyl sulfide and thioanisole in MeCN sensitized by N-methylquinolinium tetrafluoborate and 9,10-dicyanoanthracene. The probable involvement of a thiadioxirane intermediate in electron transfer photooxygenations, J. Am. Chem. Soc., 2003, **125**, 16444-16454.
- 62 B. M. Aveline, S. Matsugo and R. W. Redmond, Photochemical mechanisms responsible for the versatile application of naphthalimides and naphthaldiimides in biological systems, *J. Am. Chem. Soc.*, 1997, **119**, 11785-11795.
- 63 D. M. Guldi, G. Torres-Garcia and J. Mattay, Intramolecular energy transfer in fullerene pyrazine dyads, *J. Phys. Chem. A*, 1998, **102**, 9679-9685.
- 64 J. R. Darwent, P. Douglas, A. Harriman, G. Porter and M.-C. Richoux, Metal phthalocyanines and porphyrins as photosensitisers for the reduction of water to hydrogen, *Coord. Chem. Rev.*, 1982, **44**, 83-126.
- 65 M. R. Wasielewski, Photoinduced electron-transfer reactions for artificial photosynthesis, *Chem. Rev.*, 1992, **92**, 435-461.
- 66 M. Hippler, Photochemical kinetics: Reaction orders and analogies with molecular beam scattering and cavity ringdown experiments, *J. Chem. Educ.*, 2003, **80**, 1074-1077.
- 67 D. Lavabre, V. Pimienta, G. Levy and J. C. Micheau, Reversible, mixed 1st and 2nd order and autocatalytic reactions as particular cases of a single kinetic rate law, *J. Phys. Chem.*, 1993, **97**, 5321-5326.
- 68 L. N. Ismail, H. Zulkefle, S. H. Herman and M. R. Mahmood, Influence of doping concentration on dielectric, optical, and morphological properties of PMMA thin films, *Adv. Mater. Sci. Eng.*, 2012, **2012**, 605673.
- 69 W. Liu, Y. Li, K. Liu and Z. Li, Iron-catalyzed carbonylationperoxidation of alkenes with aldehydes and hydroperoxides, *J. Am. Chem. Soc.*, 2011, **133**, 10756-10759.
- 70 W.-J. Yoo and C.-J. Li, Highly efficient oxidative amidation of aldehydes with amine hydrochloride salts, J. Am. Chem. Soc., 2006, **128**, 13064-13065.
- J. W. W. Chang, T. M. U. Ton, S. Tania, P. C. Taylor and P. W.
 H. Chan, Practical copper(I)-catalysed amidation of aldehydes, *Chem. Commun.*, 2010, **46**, 922-924.

- 72 R. E. Rodríguez-Lugo, M. Trincado and H. Grützmacher, Direct amidation of aldehydes with primary amines under mild conditions catalyzed by diolefin-amine-Rh-I complexes, *Chem. Cat. Chem.*, 2013, **5**, 1079-1083.
- 73 Z. Yun-Fei, B. Wu and Z.-J. Shi, Ir-catalyzed C-H amidation of aldehydes with stoichiometric/catalytic directing group, *Chem. Eur. J.*, 2016, **22**, 17808-17812.
- 74 S. Debbarma and M. Sudan Maji, Cp*Rh-III-catalyzed directed amidation of aldehydes with anthranils, *Eur. J. Org. Chem.*, 2017, 3699-3706.
- 75 N. Mataga, T. Asahi, Y. Kanda, T. Okada and T. Kakitani, Mechanisms of the strongly exothermic charge separation reaction in the excited singlet-state – picosecond laser photolysis studies on the aromatic hydrocarbon tetracyanoethylene and aromatic hydrocarbon pyromellitic dianhydride systems in polar solutions, *Chem. Phys.*, 1988, 127, 249-261.
- 76 J. Mattay and M. Von den Hof, Contact and solvent-separated radical ion-pairs in organic photochemistry, *Topics Curr. Chem.*, 1991, **159**, 219-255.
- 77 A. C. Benniston, A. Harriman, P. Li, J. P. Rostron, H. J. van Ramesdonk, M. M. Groeneveld, H. Zhang, H. and J. W. Verhoeven, Charge shift and triplet state formation in the 9mesityl-10-methylacridinium cation, *J. Am. Chem. Soc.*, 2005, 127, 16054-16064.
- 78 W. A. Braunecker and K. Matyjaszewski, Controlled/living radical polymerization: Features, developments, and perspectives, *Prog. Polym. Sci.*, 2007, **32**, 93-146.
- 79 T. G. St Denis, T. Dai, L. Izikson, C. Astrakas, R. R. Anderson, M. R. Hamblin and G. P. Tegos, All you need is light. Antimicrobial photoinactivation as an evolving and emerging discovery strategy against infectious disease, *Virulence*, 2011, **2**, 509-520.
- 80 S. R. Lewis, S. Datta, M. H. Gui, E. L. Coker, F. E. Huggins, S. Daunert, L. Bachas and D. Bhattacharyya, Reactive nanostructured membranes for water purification, *Proc. Natl. Acad. Sci. USA*, 2011, **108**, 8577-8582.
- 81 S. Funyu, T. Isobe, S. Takagi, D. A. Tryk and H. Inoue, Highly efficient and selective epoxidation of alkenes by photochemical oxygenation sensitized by a ruthenium(II) porphyrin with water as both electron and oxygen donor, *J. Am. Chem. Soc.*, 2003, **125**, 5734-5740.
- 82 D. Tatsumi, T. Tsukamoto, R. Honna, S. Hoshino, T. Shimada and S. Takagi, Highly selective photochemical epoxidation of cyclohexene sensitized by Ru(II) porphyrin-clay hybrid catalyst, *Chem. Lett.*, 2017, **46**, 1311-1314.

Table of Contents Entry



View Article Online DOI: 10.1039/C8PP00162F