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Catalytic photoinduced electron transport across a lipid bilayer mediated by a membrane-soluble electron relay

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B. Limburg, E. Bouwman, S. Bonnet*

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Unidirectional photocatalytic electron transfer from a hydrophilic electron donor encapsulated in the interior of a liposome, to a hydrophilic electron acceptor on the other side of the membrane, has been achieved using the simple membrane-soluble electron relay 1-methoxy-N-methylphenazinium (MMP⁺). The total amount of photoproduct (>140 nmol) exceeds the number of moles of MMP⁺ present (125 nmol), thus showing that the transport of electrons is catalytic.

To accomplish efficient artificial photosynthesis, two complimentary redox reactions must be fuelled by visible light irradiation. In both photoreactions the generation of a long-lived charge-separated species is required, and the greatest challenge in photocatalysis is to overcome charge recombination. In order to do so, the reduced electron acceptor and the oxidized electron donor must be physically separated. In green plants for example such separation is realized by large protein molecules embedded in the thylakoid membrane of chloroplasts. The dissymmetry of biological membranes allows for unidirectional electron transfer to occur from the lumen to the stroma. However, such photocatalytically active protein assemblies are highly complex and fragile, and artificial systems based on simpler, more robust molecules are required for building artificial devices capable of solar fuel production.

Among the numerous tools offered by supramolecular photocatalysis liposomes holds great promise.¹ They offer a simple way to organize molecular components in space and mimic biological photosynthesis. By segregating electron donors and acceptors on each side of a lipid membrane, it should be possible to create long-lived charge-separated states that, in combination with two different catalysts, would allow

for producing solar fuels.¹ Electron transfer across the liposomal membrane to electron acceptors such as quinones,² Co(bpy)₃³⁺,³ or viologens⁴ has been investigated intensively in the past. However, especially with viologens some ambiguity about the true nature of the charge separation was later revealed.⁵ It was shown that in those systems electron transport occurred due to diffusion of the reduced electron acceptor through the membrane, after which it remained occluded in the interior of the liposome. Thus, because the electron-transporting molecule never returned to its original location, it was unable to turn over for producing a true catalytic reaction. Up to now, there are only few systems known in the literature that catalytically transport electrons across membranes.^{2a, 2d-f, 6} However, all of them contain a complicated molecular structure to realize the charge separation across the membrane.

Herein, we report the truly catalytic unidirectional photoinduced electron transfer from the interior of a liposome to its exterior, based largely on commercially available compounds. This study is inspired by the widely used "WST-1" cell-counting assay, in which a water-soluble electron acceptor, the 2-(4-iodophenyl)-3-(4-nitrophenyl)-5-(2,4-disulfophenyl)-2H-tetrazolium anion (WST1⁻, Scheme 1), is reduced to the corresponding formazan dye (Fz1²⁻, Scheme 1) by addition of two electrons and one proton. Usually the electrons and protons are generated inside living cells in the form of nicotinamide adenine dinucleotide (NADH), which is too hydrophilic to cross the cell membrane. The WST-1 assay requires the membrane-soluble relay 1-methoxy-N-methylphenazinium cation (MMP⁺, Scheme 1) to transport the biological reducing equivalents from inside the cell to the WST1⁻ acceptor situated on the other side of the membrane.⁷ By analogy, we envisioned that biomimetic liposomes containing a water-soluble electron donor in their interior (ethylenediaminetetraacetic acid, H₄EDTA) and a photosensitizer in the membrane would be able to unidirectionally transport the photoelectrons to the WST1⁻ molecules located outside the liposomes, provided that MMP⁺ is added to the system.⁷ We describe below photocatalytic

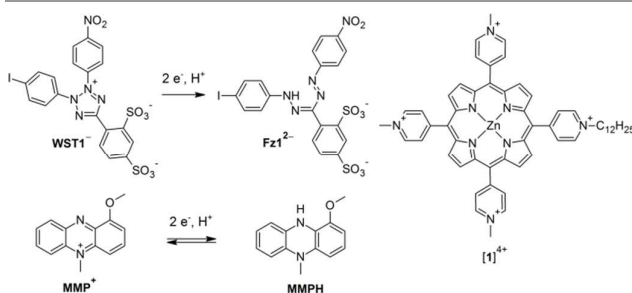
Leiden University, Leiden Institute of Chemistry, Gorlaeus Laboratories, P.O. Box 9502, 2300 RA Leiden.

Email: bonnet@chem.leidenuniv.nl

Electronic Supplementary Information (ESI) available: photocatalytic results in the presence of O₂ or in the absence of electron acceptor WST1⁻. Detailed experimental procedures.

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studies showing that the lipid membrane diminishes product inhibition, while the use of membrane-insoluble electron donors and acceptors allows for avoiding the mechanistic ambiguities generally associated with this type of studies.



Scheme 1. Chemical structures of the membrane-insoluble electron acceptor 2-(4-iodophenyl)-3-(4-nitrophenyl)-5-(2,4-disulfoxyphenyl)-2H-tetrazolium anion (WST1⁻), the membrane-soluble electron relay 1-methoxy-N-methylphenazinium cation (MMP⁺), their reduction products Fz1²⁻ and MMPH, respectively, and the lipophilic zinc porphyrin photosensitizer [1]⁴⁺.

Dye-functionalized liposomes were prepared in which the amphiphilic photosensitizer [1]⁴⁺ (Scheme 1) was added in the membrane, the electron donor HEDTA³⁻ was placed in the inner water pool of the liposome, and the electron acceptor WST1⁻ was added into the bulk solution, *i.e.*, on the outside of the liposome. The liposome bilayer composition consisted of 1,2-dipalmitoyl-*sn*-glycero-3-phosphocholine (DPPC), 1.6 mol% of the alkyl-functionalized zinc porphyrin [1]Cl₄, and 1 mol% of the pegylated lipid sodium N-(carbonylmethoxypolyethylene glycol-2000)-1,2-distearoyl-*sn*-glycero-3-phosphoethanolamine (NaDSPE-PEG2K) to stabilize the liposome dispersion. The liposomes were prepared by standard extrusion methods in an HEDTA³⁻ buffer at pH = 8, and were subsequently purified by size-exclusion chromatography to remove non-encapsulated HEDTA³⁻ (see ESI). To this liposomal solution (called hereafter liposome sample **LA**) was then added an isotonic solution containing the electron acceptor WST1⁻ (as the sodium salt), the electron relay MMP⁺ (as methylsulfate salt), and ZnSO₄. The addition of Zn²⁺ ions allowed for binding and thus inactivating traces of HEDTA³⁻ that may remain in the bulk aqueous phase after size-exclusion chromatography.^{4g, 4h} The resulting mixtures, called system **LA**₁ or **L**₂**A**₁ (see compositions in Table 1), were de-aerated and irradiated in the Soret band of [1]⁴⁺ (λ_{irr} = 449 nm). The excited photosensitizer was assumed to not differ significantly from the well-characterized methyl analogue [ZnTMPyP]⁴⁺, *i.e.*, to be of triplet character and to have an oxidation potential of ~ +0.8 V vs. NHE and a reduction potential of ~ -0.45 V vs. NHE.⁸

A typical evolution of the UV-vis spectrum of the irradiated dispersions as a function of irradiation time is shown in Figure 1a. Clearly, a band ascribed to the Fz1²⁻ dye arises at λ_{max} = 438 nm as a result of the photoinduced reduction of WST1⁻.⁷ The amount of photoproduct, n_{Fz1²⁻}, determined by the absorbance due to Fz1²⁻ (ε₄₃₈ = 37,000 M⁻¹·cm⁻¹),⁷ was plotted as a function of the number of photons Q(t) absorbed by system since t = 0 (Figure 1b, **L**₂**A**₁). The slope of this curve at t = 0 was

determined to be 1.2(1)% in both **LA**₁ and **L**₂**A**₁. However, as only half of the photosensitizers are assumed to participate in the reaction, only half of the photons are effectively used. The quantum yield for Fz1²⁻ formation, φ₀, is thus twice higher (2.4(2)%). Dynamic light scattering analysis of the mixture before and after 60 min irradiation gave essentially the same results (Z_{ave} = 166 nm, PDI = 0.13 before; Z_{ave} = 162 nm, PDI = 0.16 after), indicating that the liposomes stayed intact during photocatalysis. Sample **LA**₁ is thus able to photocatalytically transport the reducing equivalents from inside the liposomes (HEDTA³⁻) to the outside (WST1⁻), thus realizing transmembrane charge separation. In **L**₂**A**₁, the twice-higher liposome concentration allowed for observing that more Fz1²⁻ was produced during the reaction (141 nmol after 1 hour of irradiation) than the number of moles of MMP⁺ present (125 nmol) in the system (Figure 1b), indicating that MMP⁺ functioned as a true catalyst in this system.

Table 1. Bulk concentrations and initial quantum yields for the different photocatalytic liposomes described in this report.

System ^a	MMP ⁺ (μM) ^b	Triton X-100 (μM)	O ₂	EDTA (mM)	ZnSO ₄ (mM)	φ ₀ (%)
LA ₁	42	-	-	^c	5	2.4
LA ₂	-	-	-	^c	5	-
L ₂ A ₁ ^d	42	-	-	^c	5	2.4
L ₂ A ₂ ^d	-	-	-	^c	5	-
LA ₃	42	0.3	-	^c	5	-
L ₂ A ₄ ^d	42	-	yes	^c	5	-
LB ₁	42	-	-	125	-	0.90
LB ₂	-	-	-	125	-	0.72
LB ₃	-	0.3	-	125	-	3.8
LB ₄	-	-	yes	125	-	0.84

^a For the preparation of liposome samples **LA** and **LB**, see ESI. Bulk concentrations before extrusion and/or size exclusion: DPPC (1.04 mM), NaDSPE-PEG2K (10.4 μM), [1]Cl₄ (16.7 μM). Final concentration of [1]Cl₄ ~2.1 μM, as determined by UV-vis. ^b MMP⁺ added as methylsulfate salt. ^c For these samples, Na₃HEDTA was encapsulated inside the liposomes. To obtain the same osmolality inside and outside the liposomes, all solutions were prepared using isotonic NH₄OAc (379 mOsm, pH = 7). ^d these samples contained twice more liposomes per unit volume than **LA**₁ (DPPC: 2.08 mM, NaDSPE-PEG2K: 20.8 μM, [1]Cl₄: 33 μM).

When the electron relay MMP⁺ was omitted from **L**₂**A**₁ (system **L**₂**A**₂, see Table 1), formation of Fz1²⁻ was not observed. Instead the Soret band of the porphyrin bleached to around half of its initial intensity (Figure S1a). It was thus clear that system **LA**₁ requires MMP⁺ to perform charge separation, and that the electrons cannot be transferred directly from HEDTA³⁻ to WST1⁻ because they are positioned in two different aqueous phases separated by an impermeable lipid membrane. Furthermore, in **L**₂**A**₂ only half the porphyrin molecules were bleached, probably those on the inside of the membrane that were photoreduced by HEDTA³⁻. In system **LA**₃, triton X-100 was added to **LA**₁ prior to the reaction, resulting in disruption of the liposomes and release of HEDTA³⁻

into the bulk solution. In such conditions neither formation of $Fz1^{2-}$, nor bleaching of the porphyrin was observed upon light irradiation. Since the bulk concentration of $HEDTA^{3-}$ was 0.11 mM (see ESI), *i.e.* ~ 50 times lower than the bulk concentration of Zn^{2+} , the released $HEDTA^{3-}$ was fully bound to the Zn^{2+} ions thereby losing its ability to donate electrons in system LA_3 .

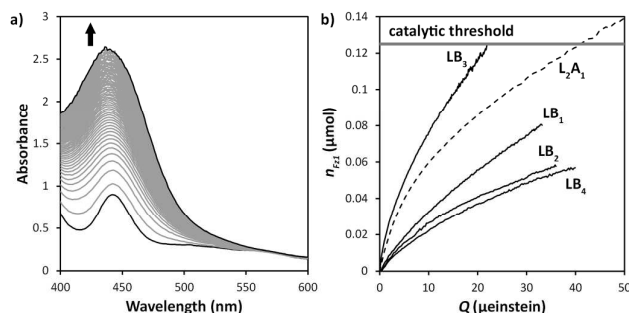


Figure 1. a) Evolution of the UV-vis spectrum of L_2A_1 (see Table 1) under blue light irradiation. Spectra were recorded every minute. b) Photocatalytic formation of $Fz1^{2-}$ (n_{Fz1}) as a function of the amount of photons $Q(t)$ absorbed by the porphyrin since $t=0$. See Table 1 for the composition of systems L_2A_1 and L_2A_4 . Conditions: $T = 298$ K, $\lambda_{irr} = 449$ nm, $\Delta\lambda_x = 25$ nm, photon flux $\Phi = 3.3 \cdot 10^{-8}$ einstein $\cdot s^{-1}$. Total irradiation time is 30 minutes, or shorter if the absorbance of the solution became higher than $A = 3$ at 438 nm.

In order to investigate in which way physical separation of the electron donor and acceptor by the lipid membrane influences the rate of the photocatalytic reaction, the photocatalytic system LB_1 was developed, which contained both the electron donor and acceptor on the outside of the liposome membrane (Figure 2, bottom). The liposomes used for these systems, called liposome sample LB , were prepared by standard extrusion methods from a lipid film of DPPC, 1 mol% NaDSPE-PEG2K and 1.6 mol% $[1]Cl_4$ hydrated in aqueous NH_4OAc ($pH = 7.0$). To this liposomal solution were added an isotonic $HEDTA^{3-}$ buffer at $pH=8.0$, $WST1^-$, and the electron relay MMP^+ , to form system LB_1 (see Table 1). System LB_1 was deaerated and irradiated as described above, which also led to the formation of $Fz1^{2-}$. A much lower initial photoelectron transfer quantum yield $\varphi_0 = 0.90(9)\%$ was found for this system compared to LA_1 , indicating that the physical separation of the electron donor and acceptor in LA_1 leads to a more stable separation of charges (Figure 1b). In system LB_1 , the photoreduced electron acceptor $Fz1^{2-}$ is in the same aqueous phase as the photosensitizer, so that it may also serve as an electron donor and quench the porphyrin excited state, or react with porphyrin cation radicals. Such reactions diminish the overall quantum yield of the photoreaction. When MMP^+ is left out from this mixture (system LB_2), the reaction is only slightly inhibited ($\varphi_0=0.72\%$) compared to LB_1 (Figure 1b), confirming that electron transfer from $HEDTA^{3-}$ to $WST1^-$ in LB_1 occurs within a single aqueous phase where no membrane needs being crossed. The addition of triton X-100 to system LB_1 (*i.e.*, system LB_3) leads to an increase in the efficiency of the photoreaction, confirming that in LA_3 triton X-100 quenches the photoreaction solely by disrupting the liposomes.

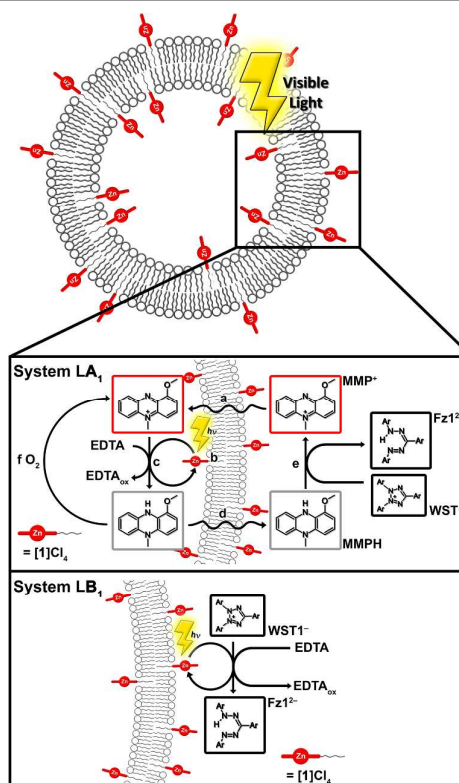


Figure 2. Top: Scheme of the photocatalytic reduction of $WST1^-$ by $HEDTA^{3-}$ with dye-functionalized liposomes. Middle: system LA_1 , with $EDTA$ and $WST1^-$ on opposite sides of the membrane. a, passive diffusion of MMP^+ through the membrane into the liposome. b, absorption of light by $[1]^{4+}$. c, photocatalytic oxidation of $EDTA$ (in the form of $HEDTA^{3-}$ at $pH 8$) and reduction of MMP^+ to $MMPH$. d, passive diffusion of $MMPH$ through the membrane. e, chemical (dark) reduction of $WST1^-$ to $Fz1^{2-}$ by $MMPH$. f, undesired re-oxidation of $MMPH$ to MMP^+ by molecular oxygen in system LA_4 . Bottom: system LB_1 , with $HEDTA^{3-}$ and $WST1^-$ on the same side of the membrane. MMP^+ has been left out for clarity as it does not influence the system significantly.

Many photocatalytic systems are not active in the presence of dioxygen, which would pose a problem in a photocatalytic fuel production system based on water oxidation. Thus, the sensitivity of systems LA_1 and LB_1 to O_2 was investigated. When system LB_1 was not deaerated (system LB_4) the presence of O_2 did not significantly influence the rate of the photoreaction, nor did it cause any induction period common to this type of systems due to the initial competition between $WST1^-$ and O_2 to accept the first photoelectrons.^{4g, 9} In contrast, when system L_2A_1 was not deaerated (system L_2A_4) complete bleaching of the Soret band of the porphyrin was observed and no $Fz1^{2-}$ was produced (Figure S1b). The striking difference between systems L_2A_4 and L_2A_1 shows that one of the catalytic intermediates in LA_1 and L_2A_2 is unstable in the presence of O_2 . We hypothesized that such an intermediate would be $MMPH$, as it plays a key role in the photocatalytic mechanism of system LA_1 . In a control experiment, system LA_1 without $WST1^-$ was irradiated in the absence of O_2 ; in this reaction $MMPH$ was produced, which could be detected by UV-vis spectroscopy (Figure S2, left). After bubbling air through the solution the reaction was fully reversed: all $MMPH$ was oxidized back to MMP^+ (Figure S2, right). Thus,

photocatalytic electron transfer through the membrane such as that observed in system **L₂A₁** is sensitive to dioxygen because the reduced electron relay is rapidly oxidized by air.

Based on the observations described above the mechanism depicted in Figure 2 (middle) is proposed for system **LA₁**. First MMP⁺, introduced in the bulk aqueous phase, diffuses through the membrane into the liposomes (a),⁷ where it is photoreduced with HEDTA³⁻ (b). This reaction presumably occurs via reductive quenching of *[1]⁴⁺ by HEDTA³⁻ (high local concentration, 125 mM), followed by reduction of MMP⁺ by [1]³⁺. Oxidative quenching would be thermodynamically feasible (the redox potential of the MMP⁺/MMPH couple is +0.06V vs. NHE)¹⁰, however kinetically unlikely due to the low concentration of MMP⁺ (42 μM). MMPH produced inside the liposomes can diffuse through the membrane in absence of O₂, thus transporting the electrons and proton out of the liposome (d). Reduction of WST1⁻ by MMPH outside of the liposomes forms Fz1²⁻ (e) and regenerates MMP⁺, as reported for the WST-1 cell counting assay. MMP⁺ can then diffuse through the membrane again and turnover further. Since the amount of Fz1²⁻ produced (e), monitored by UV-vis, exceeds the amount of MMP⁺ present at the start of the reaction (Figure 1a), MMP⁺ must be concomitantly regenerated in the bulk aqueous phase, i.e., MMP⁺ must be catalytic.

In summary, unlike previous studies in which electron transfer across lipid bilayers occurred concomitantly with the stoichiometric transport and occlusion of the electron acceptor into the membrane, directional electron transfer across a DPPC bilayer is unambiguously demonstrated here by combining a membrane-soluble electron relay, hydrophilic electron donors and acceptors situated inside and outside liposomes, respectively, and a membrane-bound photosensitizer. In this system the MMP⁺ electron relay truly acts catalytically in absence of oxygen, but under air it is oxidized and cannot fulfill its electron-transporting role. Under inert atmosphere, the actual transport of electrons across the membrane does not limit the reaction rate, as the initial quantum efficiency of the reaction through the membrane (**LA₁**) is three times higher than when the donor and acceptor are both positioned on the same side of the membrane (**LB₁**). Keeping the photoreduced electron acceptor physically separated from the electron donor allows for preventing product inhibition, i.e., quenching of the porphyrin excited states by Fz1²⁻, which would otherwise diminish the quantum efficiency of the photoreduction. Finding a membrane-soluble electron relay that is stable in the presence of dioxygen will be required for the future development of supramolecular photocatalytic systems in which water oxidation and proton reduction catalysts are combined.

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