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Photosensitized Electron Transfer Catalysis of the Mukaiyama Aldol Reaction by Monocationic N^{21},N^{22}-Bridged Porphyrins

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Abstract : N^{21},N^{22}-Bridged porphyrin hydroperchlorates were converted into monocationic N^{21},N^{22}-bridged N^{23}-alkylphlorins by way of single electron transfer followed by radical coupling when irradiated with visible light in the presence of enol silanes. A small amount (0.13 mol %) of N^{21},N^{22}-bridged porphyrin hydroperchlorates catalyzed aldol reaction of aldehydes and ketones with enol silanes under the irradiation of visible light. The phlorin intermediate plays a key role in this photosensitized catalysis of the Mukaiyama aldol reactions. © 1999 Elsevier Science Ltd. All rights reserved.

Photo-induced single electron transfer (PET) reactions have been the focus of recent studies in the photochemistry of porphyrins and metalloporphyrins.[1] As PET can generate reactive radical species from various organic substrates,[2,3] porphyrins as photosensitizers are expected to promote synthetically useful reactions via a PET mechanism.[4] Although enol silanes have frequently been used in the PET reactions due to their low oxidation potentials,[2] ordinary porphyrins do not cause PET from enol silanes because of unfavorable thermodynamics in their excited states.[1b] We describe here that the photoredox property of porphyrin can be adjusted by the introduction of the N^{21},N^{22}-bridge to induce a PET reaction with enol silane and that these monocationic N^{21},N^{22}-bridged porphyrins cause efficient photosensitized catalysis of the Mukaiyama aldol reaction of enol silanes with aldehydes and ketones.[5]

We have recently shown that the monocationic N^{21},N^{22}-bridged porphyrin ((N^{21},N^{22}-(PhC=CPh)(OEP[6])$HClO_4$ (**1a**))[7a,7b] is converted into the monoprotonated 15*H*-phlorin **2** by electron transfer reduction with 1-benzyl-1,4-dihydronicotinamide (BNAH) under acidic conditions (Scheme 1).[8] The 5-cyanoOEP analogue (N^{21},N^{22}-(PhC=CPh)(5-CN-OEP)$HClO_4$ (**1b**))[7c] and the TPP[6] analogue (N^{21},N^{22}-(PhC=CPh)(TPP)$HClO_4$ (**1c**))[7d] as well as **1a** show strong fluorescence bands at ca. 650 nm and they are effectively quenched by the addition of methyl trimethylsilyl dimethylketene acetal (MSKA) in MeCN.[9] Irradiation of a mixture of **1a** and MSKA (33 equiv.) by a 150W tungsten lamp in CH_2Cl_2 for 3 min resulted in the formation of a phlorin **3a** which shows a UV-vis spectral pattern (362, 453, 541, 575, 794 nm) quite similar to that of **2** (367, 458, 545, 577, 818 nm).[8] Although **3a** could not be characterized well due to its labile nature, irradiation of N^{21},N^{22}-(EtC=CEt)(TTP[6])$HClO_4$ (**1d**) (0.012 mmol) in a degassed mixture of 1-trimethylsilyloxystyrene (SOS) (1.03 mmol) and CH_2Cl_2 (0.5 mL) under argon using a 300W xenon lamp for 30 min gave N^{21},N^{22}-bridged N^{23}-benzoylmethyl-N^{24}-trimethylsilyl-15*H*-phlorin perchlorate (**3d**) and the 10*H*-phlorin isomer (**3d**') as an unseparable mixture in a 78% yield.[10] Cu^{+2}-oxidation of these phlorins afforded N^{21},N^{22}-bridged N^{23}-benzoylmethylporphyrin perchlorate (**4d**)[10] in a 51 % isolated yield based on **1d**. Thus, the photo-induced electron transfer reaction of **1a** (or **1d**) with enol silanes would generate a porphyrin π-radical (**A**) (or (**A**'))

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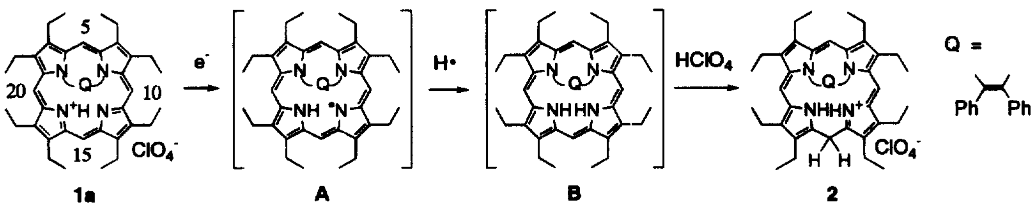
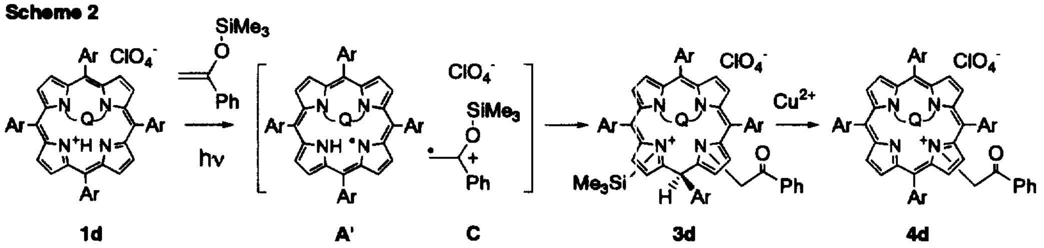
Scheme 1



Scheme 2



which was detected by ESR in the case of the electron transfer reduction of **1a** by BNAH.[8] A radical cation such as (**C**) derived from the enol silane loses trimethylsilyl cation and the resulting alkyl radical attacks on the N(23) position of the porphyrin π-radical (**A'**) to produce N^{21},N^{22}-bridged N^{23}-alkyl-15*H*-phlorin **3d** as a Me_3SiClO_4 adduct probably by way of N^{21},N^{22}-bridged N^{23}-alkyldihydroporphyrin having a 20π-electron cycloconjugation like (**B**) (see Scheme 1 and 2).

When a mixture of MSKA (2.93 mmol) and benzaldehyde (3.69 mmol) in CH_2Cl_2 (0.3 mL) were irradiated with a 300W xenon lamp at 0 °C for 10 min in the presence of 0.13 mol % of **1a**, the aldol product $PhCH(OSiMe_3)CMe_2CO_2Me$ (**5**) was afforded in a 81% isolation yield after chromatographic purification on silica gel with CH_2Cl_2. Figure 1 shows the progress of the aldol reaction between p-tolualdehyde (0.28 mmol) and MSKA (0.24 mmol) in the presence of **1a** (0.0016 mmol) in $CDCl_3$ (0.5 mL) as monitored by ^1H NMR spectroscopy. While the reaction did not occur at all in the dark, the aldol product **5'** began to form after an induction period of 20 min through the irradiation with a 150W tungsten lamp. The aldol reaction stopped when light was turned off and it restarted as soon as light was turned on. Thus, the present reaction is driven by light and, as such, it is totally different from the conventional Mukaiyama aldol reactions catalyzed by Lewis acids including Me_3SiClO_4.[5,11]

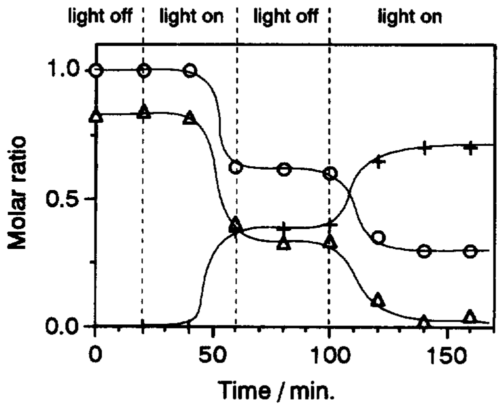


Figure 1. Light-dependence of the aldol reaction between MSKA (Δ) and p-tolualdehyde (O) to give the aldol product **5'** (+) in the presence of porphyrin **1a**.

Scheme 3

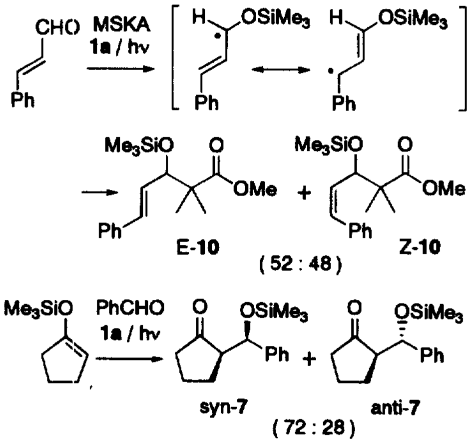


Table 1. Photosensitized catalytic aldol reaction of enol silanes with aldehydes and ketone.[a]

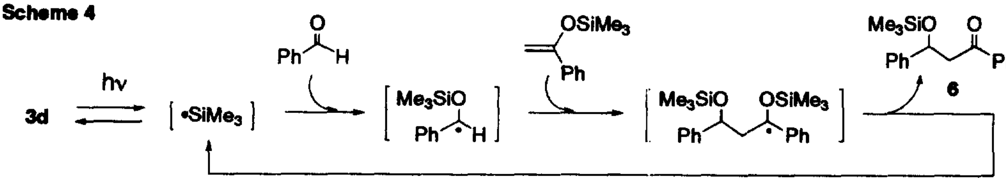
entry	enol silane	aldehyde or ketone	catalyst	time (min)	product	yield[b] (%)
1	$Me_2C{=}C(OMe)OSiMe_3$	PhCHO	**1a**	< 3	$PhCH(OSiMe_3)CMe_2CO_2Me$ (**5**)	89
2	$Me_2C{=}C(OMe)OSiMe_3$	PhCHO	none	60		0
3	$Me_2C{=}C(OMe)OSiMe_3$	PhCHO	**1a**	120		0[c]
4	$CH_2{=}C(Ph)OSiMe_3$	PhCHO	**1a**	21	$PhCH(OSiMe_3)CH_2COPh$ (**6**)	86
5	$CH_2{=}C(Ph)OSiMe_3$	PhCHO	**1b**	12	(**6**)	89
6	$CH_2{=}C(Ph)OSiMe_3$	PhCHO	**1b**	15	(**6**)	86[d]
7	$CH_2{=}C(Ph)OSiMe_3$	PhCHO	**1c**	30	(**6**)	91
8	1-($OSiMe_3$)cyclopentene	PhCHO	**1a**	60	(**7**)[e]	49[f]
9	1-($OSiMe_3$)cyclopentene	PhCHO	**1b**	60	(**7**)	58[f]
10	1-($OSiMe_3$)cyclopentene	PhCHO	**1c**	120		0
11	$Me_2C{=}C(OMe)OSiMe_3$	PhCOMe	**1a**	9	$Ph(Me)C(OSiMe_3)CMe_2CO_2Me$ (**8**)	87
12	$CH_2{=}C(Ph)OSiMe_3$	PhCOMe	**1a**	80	$Ph(Me)C(OSiMe_3)CH_2COPh$ (**9**)	88[g]
13	$Me_2C{=}C(OMe)OSiMe_3$	t-PhCH=CHCHO	**1a**	< 3	(**10**)[e]	92[h]

[a] A mixture (enol silanes/aldehyde(ketone)/catalysts = 1.0/1.1/0.0013 mmol) in a 5 mm nmr tube was irradiated through a pyrex filter by a 300-W xenon lamp with 10 cm distance at 0°C. [b] NMR yields determined relative to $C_2H_2Cl_4$ (0.10 cm^3). [c] In the dark. [d] Visible light irradiation ($\lambda > 500$ nm) through a cut-off filter. [e] see Scheme 3. [f] Syn/anti ratio = 72/28. [g] 52% conversion of enol silane. [h] Trans/cis ratio = 52/48.

The feature of this photosensitized catalysis of the aldol reaction by N^{21},N^{22}-bridged porphyrins is summarized in Table 1. The visible light irradiation ($\lambda > 500$ nm) in the presence of porphyrin catalyst is crucial for the reaction to proceed (Table 1, entry 1, 2, 3, and 5, 6). The catalytic activity as indicated by the yield and the time required to achieve complete conversion of the enol silanes follows the order: **1b** > **1a** > **1c** (entry 4, 5, 7, and 8, 9, 10),[12] and the reactivity of enol silanes (MSKA > SOS > 1-trimethylsilyloxycyclopentene (SOCP)) depends on their oxidation potentials (entry 1, 4, 8).[13] The aldol product **10** made from trans-cinnamaldehyde proved to be a mixture of an E-isomer and a Z-isomer with a ratio of 52 : 48 (Scheme 3; Table 1, entry 13). Since no photochemical trans-cis isomerization of cinnamaldehyde took place under the present reaction conditions, the lack of stereospecificity is explained in terms of the intermediacy of the achiral enol radical.[14] The syn-anti selectivity (72/28) in the aldol product **7**[15] derived from SOCP (Scheme 3; Table 2, entry 8) is analogous to that (75/25) reported for the high-pressure aldol reaction under neutral conditions[16] and is in a remarkable contrast to the ratio (25/75) in the conventional $TiCl_4$-catalyzed Mukaiyama reaction.[5] Thus, the present photocatalytic aldol reaction may involve a radical chain process taking into account its remarkable efficiency as shown in Table 1 (entry 1 and 13). The C-C bond formation of enol silanes via radical chain mechanism has recently been reported.[17] Since the reaction of the isolated phlorins **3d** and **3d'** with benzaldehyde did not give $PhCH(OSiMe_3)CH_2COPh$ (**6**) even under light irradiation, the phenacyl group bound to the pyrrole nitrogen of **3d** and **3d'** may not be the source of **6**. Provided that the Si-N bond of **3d** and **3d'** is cleaved homolytically through visible light irradiation, thus generated trimethylsilyl radical can act as a chain carrier for the aldol reaction and it would be depleted in the dark as shown in Scheme 4. The radical chain carrier would be accumulated during the induction period observed in Figure 1.

Since enol silanes and carbonyl compounds of general synthetic utility are colorless and nonluminescent, PET especially by visible light is impossible.[18] It is remarkable that N^{21},N^{22}-bridged porphyrin induces

Scheme 4



Mukaiyama aldol reaction to proceed in good yields at room temperature, under neutral conditions, and by the irradiation of visible light. It is possible to further extend the scope of synthetic application by tuning the photoredox properties of N^{21},N^{22}-bridged porphyrins.

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6. Abbreviations: OEP (octaethylporphyrin dianion); TPP (meso-tetraphenylporphyrin dianion); TTP (meso-tetra(p-tolyl)-porphyrin dianion).
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9. The rate constant ($k_q = 2.6 \times 10^9\ M^{-1}sec^{-1}$) for the fluorescence quenching of **1a** by MSKA in MeCN was determined from a Stern-Volmer plot and the fluorescence lifetime ($\tau = 5.42$ ns) of **1a**. This is consistent with the exothermic electron transfer from MSKA ($E_{1/2} = 0.92$ V vs. Ag/AgCl)[13] to the singlet excited state of **1a** ($E_{1/2}(P^{+*}/P^{\bullet}) = 1.35$ V). The latter was calculated by adding the singlet excitation energy (46.2 kcal/mol) to the ground state reduction potential ($E_{1/2}(P^{+}/P^{\bullet}) = -0.72$ V).
10. ^1H NMR data (δ, $CDCl_3$). **3d** (or **3d'**): 8.31, 8.26, 7.73, 7.61, 7.32, 7.00 (dx6, 1Hx6, pyrrole-β-H); 7.44, 7.39 (ddx2, 1Hx2, pyrrole-β-H, J = 4.2, 2.2 Hz); 8.12, 7.76, 7.63, 7.56, 7.51, 7.47 (dx6, 2Hx6, tolyl-o,m-H); 7.82 (br, 2H, tolyl-o,m-H); 6.82 (t, 1H, benzoyl-p-H); 6.51 (t, 2H, benzoyl-m-H); 5.15 (d, 2H, benzoyl-o-H); 2.07 (br, 1H, 15-meso-H); 2.64, 2.63, 2.60, 2.58 (sx4, 3Hx4, tolyl-p-CH_3); -0.20, -0.40 (tx2, 3Hx2, bridge CH_3); -0.10, -0.22, -0.75, -1.00 (mx4, 1Hx4, bridge CH_2); 0.64, -0.43 (dx2, 1Hx2, N-CH_2, J = 18.3 Hz); -0.77 (s, 9H, N-$Si(CH_3)_3$). **3d'** (or **3d**): 8.34, 8.28, 7.624, 7.49, 7.32, 7.03 (dx6, 1Hx6, pyrrole-β-H); 7.619 (dd, 1H, pyrrole-β-H, J = 5.1, 2.0 Hz), 7.34 (dd, 1H, pyrrole-β-H, J = 4.2, 2.0 Hz); 8.13, 7.62 (brx2, 2Hx2, tolyl-o,m-H); 8.02, 7.79 (ddx2, 2Hx2, tolyl-o,m-H); 7.71, 7.65, 7.50 (dx3, 2Hx3, tolyl-o,m-H); 6.91 (t, 1H, benzoyl-p-H); 6.80 (br, 2H, benzoyl-m-H); 5.74 (br, 2H, benzoyl-o-H); 2.73 (br, 1H, 10-meso-H); 2.66, 2.64, 2.60, 2.37 (sx4, 3Hx4, tolyl-p-CH_3); -0.09, -0.21, -0.73, -0.99 (mx4, 1Hx4, bridge CH_2); -0.18, -0.40 (tx2, 3Hx2, bridge CH_3); 1.02, -1.03 (dx2, 1Hx2, N-CH_2, J = 12.6 Hz); -1.41 (s, 9H, N-$Si(CH_3)_3$). **4d**: 9.11 (s, 2H, pyrrole-β-H); 8.68, 8.64, 8.61, 8.55, 8.19, 8.09 (dx6, 1Hx6, pyrrole-β-H); 8.35, 8.26, 8.02, 7.81, 7.73, 7.71 (dx6, 2Hx6, tolyl-o,m-H); 7.8~7.6 (br, 4H, tolyl-o,m-H); 6.78 (t, 1H, benzoyl-p-H); 6.19 (t, 2H, benzoyl-m-H); 4.09 (d, 2H, benzoyl-o-H); 2.77, 2.744 (sx2, 3Hx2, tolyl-p-CH_3); 2.735 (s, 6H, tolyl-p-CH_3); -1.23, -1.48 (tx2, 3Hx2, bridge CH_3); -2.52 (m, 2H, bridge CH_2); -3.54, -3.84 (mx2, 1Hx2, bridge CH_2); -3.72, -4.95 (dx2, 1Hx2, N-CH_2, J = 18.3 Hz).
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