Supporting information

Reactivity of a Pyridinium-Substituted Dimethyldihydropyrene switch under Aerobic conditions: Self-Sensitized Photo-Oxygenation and Thermal Release of Singlet Oxygen

Saioa Cobo,[a] Frédéric Lafolet,[a] Eric Saint-Aman,[a] Christian Philouze,[a] Christophe Bucher,[b] Serena Silvi,[c] Alberto Credi,[c] and Guy Royal[a]

[a] Univ. Grenoble Alpes, DCM UMR 5250, F-38000 Grenoble, CNRS, DCM UMR 5250, F-38000 Grenoble, France

[b] Laboratoire de Chimie (UMR5182), École Normale Supérieure de Lyon/CNRS Université de Lyon 1, Lyon-France.

[c] Dipartimento di Chimica ''G. Ciamician'', Universita` di Bologna, via Selmi 2, 40126 Bologna, Italy.

Table of contents

1. General Procedures and methods

General procedures and methods: All purchased chemicals and solvents were used as received except THF and diethyl ether that were distillated over sodium/benzophenone under argon. NMR spectra were recorded on a Bruker Avance-500 MHz or 400 MHz spectrometer in CD_3CN. Chemical shifts (ppm) are referenced to residual solvent peaks. Mass spectrometry analyses (ESI positive mode) were carried out at the DCM mass spectrometry facility with an Esquirre 3000 Plus (Bruker Daltonics). Absorption spectra were recorded using either a Varian Cary 50 Scan or a Varian Cary 300 UV-visible spectrophotometer equipped with a temperature controller unit. Luminescence spectra in the NIR were recorded on an Edinburgh Instruments FLS-920 spectrometer equipped with a Ge detector cooled at 77K.

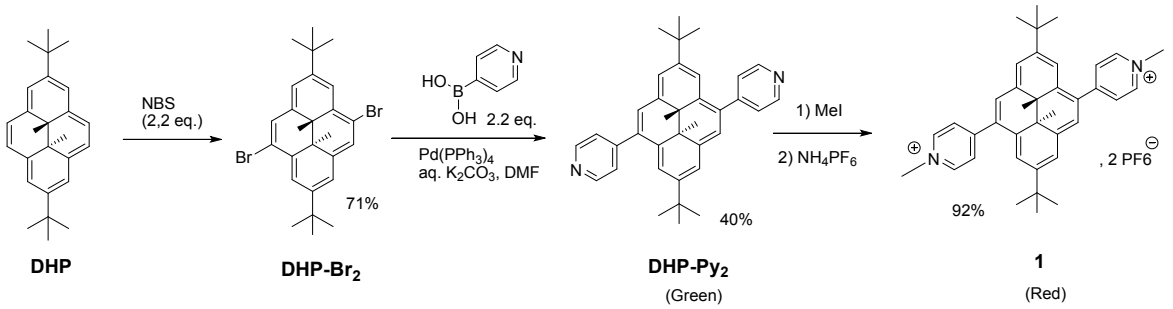
Irradiation experiments have been conducted either under inert atmosphere using a Jaram glove box with carefully degassed solvents or under air (1 atm). Visible irradiations experiments have been carried out with a Xe-Hg lamp, using a 630 nm cut-off filter unless otherwise stated and the samples have been placed in a water bath (room temperature (23°C) or 8°C). Samples have been placed at a distance of 15 cm of the visible lamp. The reactions have been investigated from UV-visible and NMR experiments. Intermediate spectra have been recorded at different times depending on the isomerization process rates. The ratio between the different forms has been determined by ^{1}H-NMR from the relative integration of the characteristic resonance peaks of the N^+-Me methyl groups of the different forms.

Data for single crystal X-Ray diffraction have been collected at 200 K on a Bruker AXS Enraf-Nonius Kappa CCD diffractometer using the Mo-Kα radiation from an Incoatec microsource. Intensity data were collected for Lorentz-polarization effects and absorption

with the Olex 2 package. Structures solutions and refinements were performed with the SHELX software by directs methods. All non-hydrogen were refined by full matrix least-squares with anisotropic thermal parameters. Hydrogen atoms were introduced at calculated positions as riding atoms. Crystallographic structures were drawn with the Mercury 3.1 software. A summary of the data collection and structure refinements is provided in the supplementary information. CCDC 1042148 contains the crystallographic data for this **2** and **2-O$_2$** (as PF_6^- salts). These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. Crystals containing both **2** and **2-O$_2$** (~50%-50%) have been grown over a one month period by slow diffusion at low temperature (-40°C) of diethyl ether in a CH_3CN solution of freshly prepared **2-O$_2$**. We observed polymorphism and obtained at least two kinds of crystals. The structures reported here have been obtained with poorly stable monoclinic crystals, P21/c, a=15.137(3) Å, b=14.675(3) Å, c=13.735(3) Å, β=114.58(3)°, V= 2774.5(9) Å3, displaying compounds **2** and **2-O$_2$** as a blend, one disordered ether molecule and one acetonitrile molecule in the asymmetric unit. The fragile polymorph crystals were twinned orthorhombic, Pbca, a=12.317(3) Å, b=13.689(3) Å, c=22.848(5) Å, V= 3852.5(13) Å^3, with no solvent molecule in the asymmetric unit. This allowed us to perform a 200 K measurement giving very similar results to structures reported here but also an annealing experiment (warming at 297 K for 2 days and the cooling back to 200 K) which gave us the DHP model. Unfortunately due to the twinning and to the weakness of the diffracting power of these crystals, these data were not good enough for publication.

2. Preparation of 1, 2 and 2-O_2.

1 was prepared as represented in Scheme S1, following a modified reported procedure.[1]



Scheme S1. Preparation of **1**.

2,7-Di-tert-butyl-trans-10b,10c-dimethyl-10b,10c-dihydropyrene (DHP), and 4,9-dibromo-2,7-di-tert-butyl-trans-10b,10c-dimethyl-10b-10c dihydropyrene (DHP-Br_2) were synthesized following previously reported procedures.[2]

2,7-di-tert-butyl-4,9-di-(4-pyridyl)-trans-10b,10c-dimethyl-10b,10c-dihydropyrene (DHP-Py_2). A round bottom flask was filled under an argon atmosphere with 4,9-dibromo-2,7-di-tert-butyl-trans-10b,10c-dimethyl-10b,10c-dihydropyrene (0.100 g, 0.2 mmol), 4-pyridinylboronic acid (52 mg, 0.42 mmol) and freshly distilled THF (6 mL). A degassed aqueous solution (2 mL) of sodium carbonate (0.1 g, 0.95 mmol) and $Pd(PPh_3)_4$ (35 mg, 0.03 mmol) was then added into the flask and the resulting mixture was heated under stirring for 48 h. After cooling the mixture to room temperature, the solvent was evaporated under reduced pressure and the residue was then dissolved in water and extracted with dichloromethane. The solution was dried over anhydrous $MgSO_4$, filtered and the solvent was evaporated under reduced pressure. Around 5 mL of diethyl ether were added to the crude product and the insoluble **DHP-Py_2** was then filtered and dried under vacuum. **DHP-Py_2** was isolated as a dark brown solid (40 mg, 40% yield). **DHP-Py_2**: ^{1}H NMR (400 MHz, 298 K,

$CDCl_3$) δ (ppm): -3.68 (s, 6H), 1.61 (s, 18H), 7.78 (m, 4H), 8.48 (s, 2H), 8.60 (s, 2H), 8.64 (s, 2H), 8.85 (m, 4H). ESIMS: m/z: calcd for $C_{36}H_{38}N_2$ $+H^+$: 499.7 [$M+H^+$] found: 499.4. Exact mass (M^+) calc.: 499.3107, found: 499.3105. Anal. Calc. for $C_{36}H_{38}N_2 \bullet 0.5H_2O$: C, 85.16; H, 7.74; N, 5.52; found: C, 85.16; H, 7.96; N, 5.10. 5o: RMN 1H (400 MHz, 298 K, $CDCl_3$) δ (ppm): 1.18 (s, 18H), 1.54 (s, 6H), 6.57 (d, J = 2Hz, 2H), 6.84 (s, 2H), 6.86 (d, J = 2Hz, 2H), 7.48 (m, 4H), 8.61 (m, 4H).

2,7-di-tert-butyl-4,9-di-(N-methylpyridin-4-yl)-trans-10b,10c-dimethyl-10b,10c-dihydropyrene hexafluorophosphate (1, 2 PF_6^-). 35 mg of DHP-Py_2 (0.070 mmol) were dissolved in 20 mL CH_2Cl_2. 1 mL of CH_3I was then rapidly added and the solution was refluxed for two hours. Upon cooling down to room temperature, the precipitate formed (iodide salt) was filtered off, washed with cold CH_2Cl_2 and dissolved in 40 mL CH_3OH. Addition of a saturated aqueous solution of NH_4PF_6 precipitated the hexafluorophosphate salt of **1** as a red-brown solid that was collected by filtration, washed with cold water and CH_3OH and dried under vacuum. Crystals could be obtained by slow diffusion of diethyl ether into a CH_3CN solution of **1** (yield 92%, 45 mg, 64.4 µmol). **1**: ^1H NMR (500 MHz, 298 K, CD_3CN) δ (ppm): -3.63 (s, 6H), 1.65 (s, 18H), 4.43 (s, 6H), 8.45 (m, 4H), 8.70 (s, 2H), 8.73 (s, 2H), 8.79 (m, 4H), 8.89 (s, 2H). Exact mass: m/z: calcd for $C_{38}H_{44}N_2^{2+}$: 264.1747 [$M-2PF_6^-$], found: 264.1750.

2 and **2-O_2** were generated by visible irradiation of a solution of **1** under inert atmosphere and under air following the procedure described further. They can be isolated in the solid state (**2**: orange powder; **2-O_2**: yellowish powder) by evaporation at 0°C of freshly prepared solutions of **2** and **2-O_2** respectively.

2: ^{1}H NMR (500 MHz, 298 K, CD_3CN) δ (ppm): 1.20 (s, 18H), 1.50 (s, 6H), 4.26 (s, 6H), 6.69 (s, 4H), 7.12 (s, 2H), 7.37 (s, 2H), 8.06 (m, 4H), 8.49 (m, 4H). Mass (m/z): calcd: 673.3 [M-PF_6^-], found: 673.3.

2-O_2: ^{1}H NMR (500 MHz, 298 K, CD_3CN) δ (ppm): -0.05 (s, 3H), 1.04 (s, 9H), 1.24 (s, 9H), 2.07 (s, 3H), 4.24 (s, 3H), 4.28 (s, 3H), 6.51 (s, 1H), 7.00 (s, 1H), 7.06 (d, J = 2.1 Hz, 1H), 7.22 (d, J = 2.1 Hz, 1H), 7.42 (d, J = 2.1 Hz, 1H) 7.64 (s, 1H) 7.88 (d, J = 7.0 Hz, 2H), 8.07 (d, J = 7.0 Hz, 2H), 8.49 (d, J = 7.0 Hz, 2H), 8.54 (J = 7.0 Hz, 2H). Mass (m/z): calcd: 705.3 [M-PF_6^-], found: 705.3.

3. Irradiation procedures:

Samples for experiments under inert atmosphere were prepared in a Jaram glove box with carefully degassed solvents, or were thoroughly purged with argon. Solutions for experiments in the presence of oxygen were prepared under air (1 atm). The solutions were irradiated in UV-visible quartz cells or NMR tubes. The concentration used for UV-visible spectroscopy and NMR experiments were comprised between 2 x 10^{-5} M and 3 x 10^{-3} M. The visible irradiations for making the isomerization of the "closed" **1** isomer to its corresponding "open" **2** were carried out with a Xe-Hg lamp, using a 630 nm cut-off filter and the samples were placed at 8°C bath in order to limit the reverse thermal reaction. Samples were placed at a distance of 15 cm of the visible lamp. Alternatively, irradiation was performed at room temperature with a 150 W tungsten-halogen lamp equipped with a 590 nm cut-off filter.

The conversions between the different species were investigated from UV-visible and NMR experiments. Intermediate spectra were recorded at different times depending on the isomerization processes rates. The ratio between the different species was determined by ^{1}H-

NMR from the relative integration of the characteristic resonance peaks of the N^+-CH_3 groups of the different forms.

4. Phosphorescence measurements.

Luminescence measurements in the near infrared (NIR) region were performed with an Edinburgh Instruments FLS-920 spectrometer equipped with a germanium detector cooled with liquid nitrogen. The luminescence was recorded on air-equilibrated CD_3CN solutions contained in 3-mL quartz cells with 1-cm path length. Deuterated acetonitrile was used as the solvent to increase the sensitivity of the measurement, owing to the significantly higher emission quantum yield of singlet oxygen in comparison with CH_3CN. Compound **2-O_2** was generated in situ by exhaustive irradiation of **1** in the visible region (ca. 60 min irradiation under the conditions employed) at room temperature. The solution was then warmed up at 60°C and its luminescence properties (spectral dispersion and time dependence of the intensity) were monitored in the absence of photoexcitation (the excitation source of the spectrometer was turned off).

5. ^{1}H NMR spectra of 1, 2 and 2-O_2.

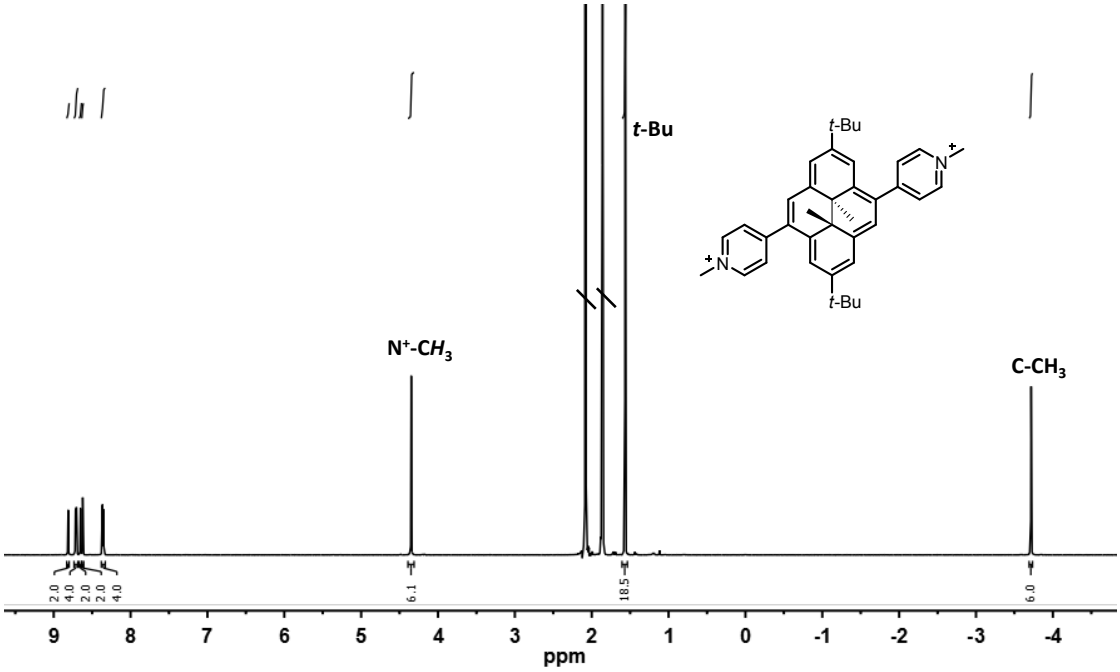


Figure S1. ^{1}H-NMR spectra of **1** in CD_3CN.

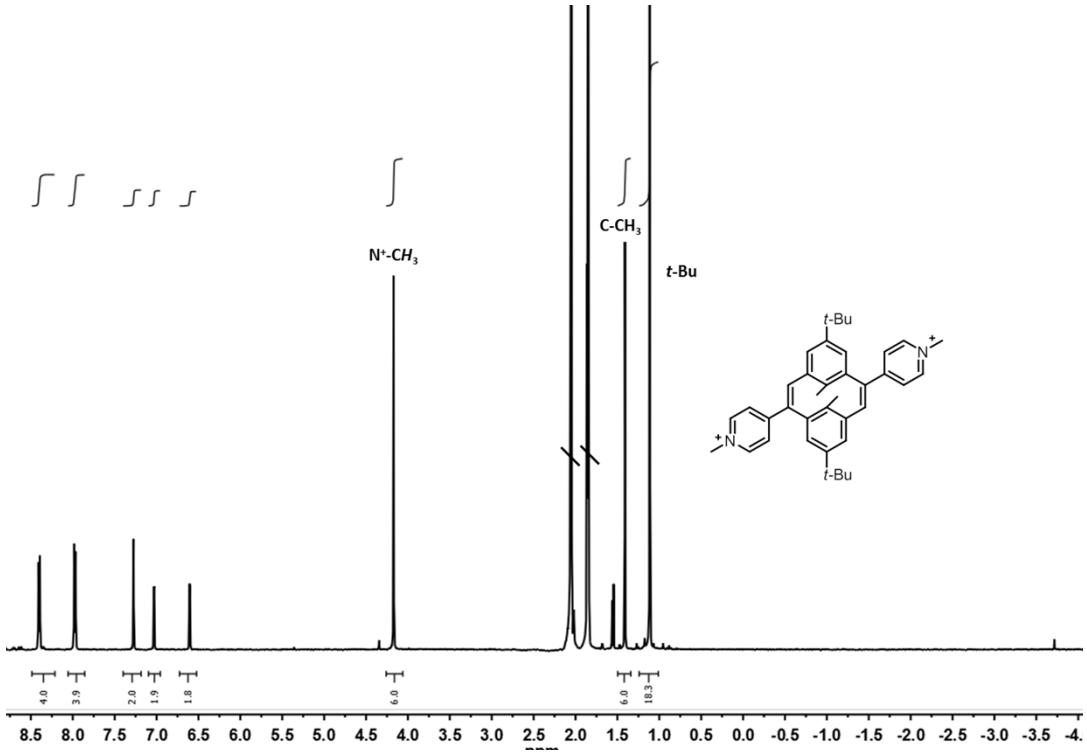


Figure S2. ^{1}H-NMR spectra of **2** in CD_3CN.

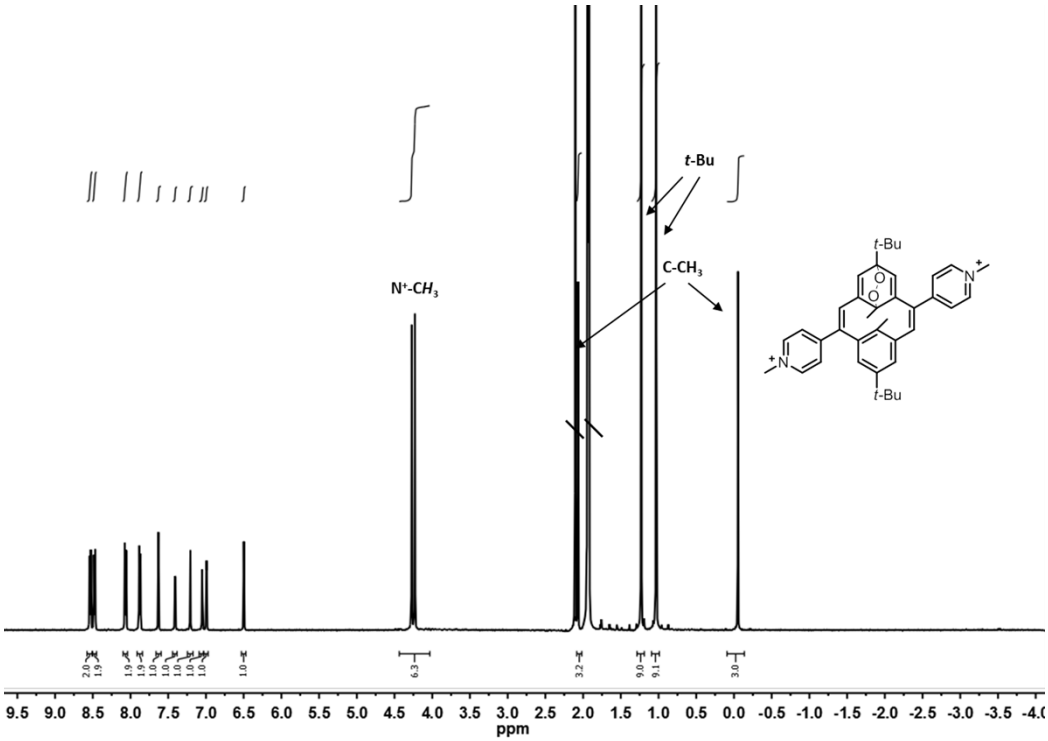


Figure S3. ^{1}H-NMR spectra of **2-O$_2$** in CD_3CN.

6. Mass spectrum of a solution of 2-O$_2$.

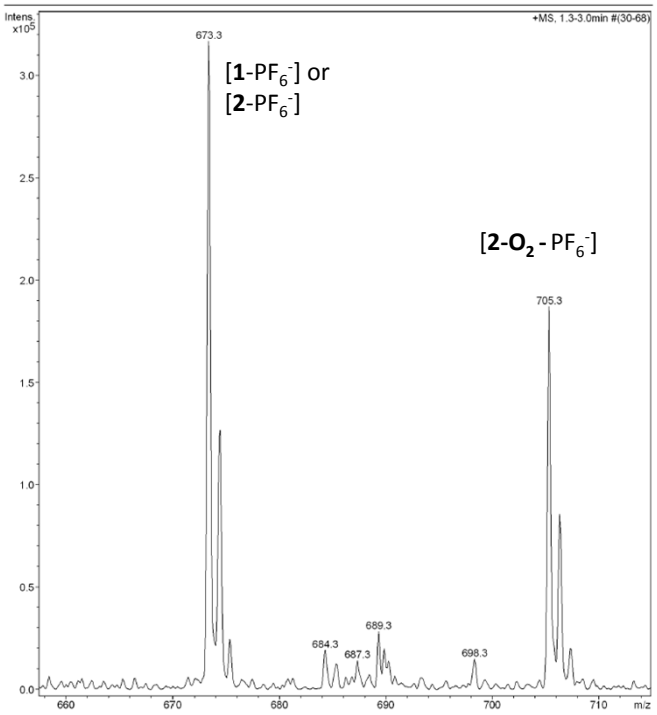


Figure S4: Experimental electrospray ionization mass spectra of a solution of **2-O$_2$** in CH_3CN. Because of the thermal return reactions, the presence of **1** and/ or **2** is also detected.

7. UV-visible spectra of 1, 2 and 2-O_2

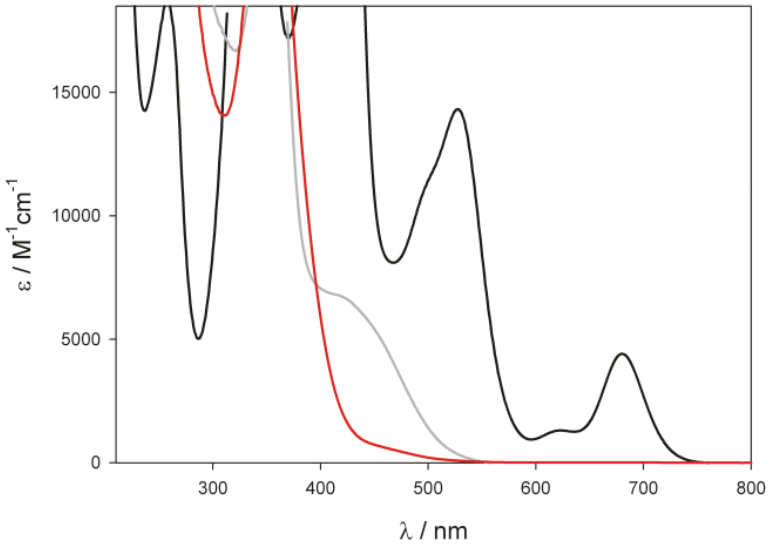
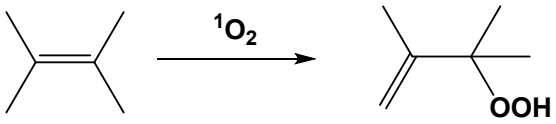


Figure S5. Absorption spectra in CH_3CN of **1** (black), **2** (gray) and **2-O_2** (red).

8. ^{1}H NMR analysis of singlet oxygen trapping

Singlet oxygen trapping experiments were carried out by NMR using 2,3-dimethyl-2-butene following the procedure previously described (W. Fudickar and T. Linker, *Chem. Eur. J.*, 2011, **17**, 13661-13664.).



A solution of **1** (3 mM) in CD_3CN was irradiated (λ>630nm) and converted into **2-O_2**. A 30 fold excess (90 mM) of 2,3-dimethyl-2-butene was added to the solution and the sample was maintained at 35°C in the dark. After 48 h, a ^{1}H NMR spectra was acquired with simultaneous saturation of the large signal at 1.8 ppm due to unreacted 2,3-dimethyl-2-butene. The two olefin proton signals for trapped hydroperoxide appear in the open window of 4.88 - 4.93 ppm. Comparison of the average peak integrals with signals of regenerated **1** showed that 80±12 % of the released singlet oxygen was trapped.

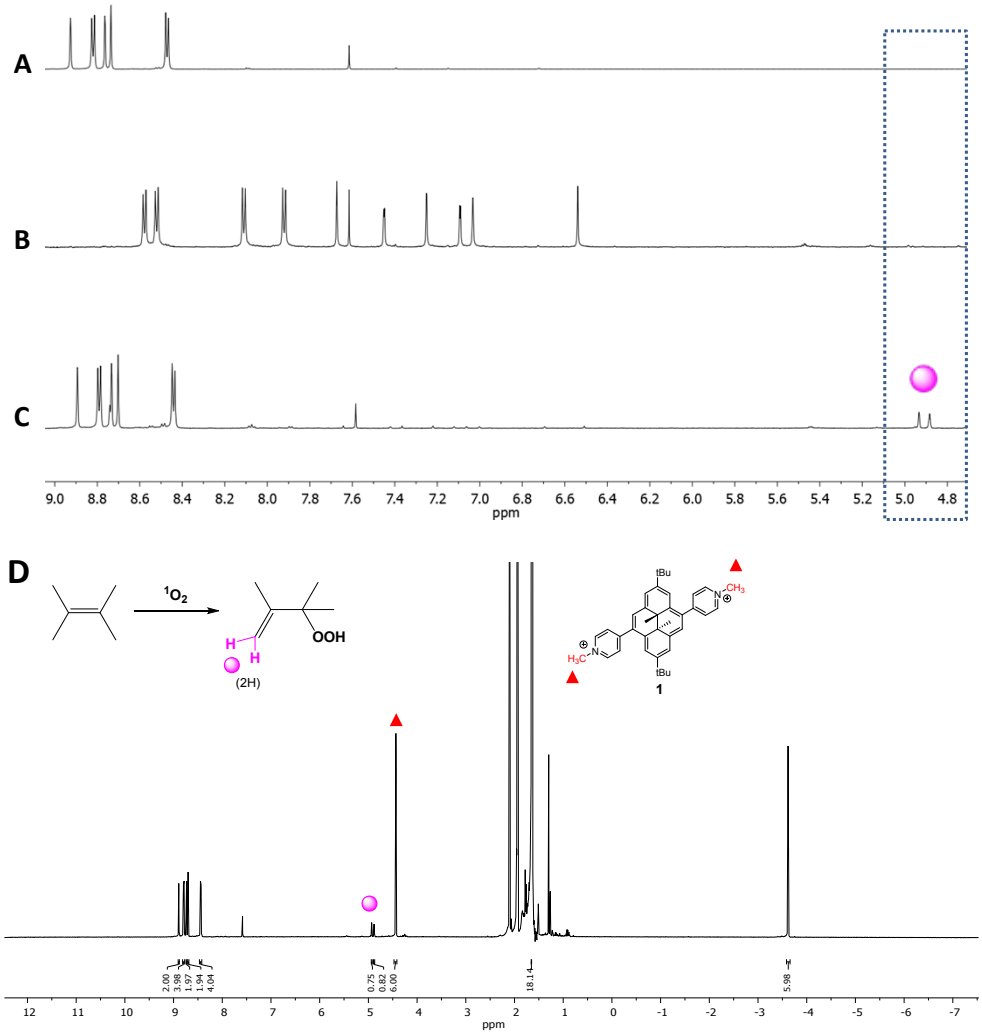


Figure S6. Partial ^{1}H NMR spectra of : (A) **1**, (B) Photogenerated **2-O$_2$**, and (C) reaction mixture in CD_3CN after complete cycloreversion of **2-O$_2$** back to **1** in the presence of 30-fold excess 2,3-dimethyl-2-butene. (D) Full spectrum after complete cycloreversion of **2-O$_2$**. Colored balls in C and D: signals at 4.88 and 4.93 ppm that correspond to the two olefin protons for trapped product

9. ^{1}H NMR analysis of photosensitizing properties of 1 towards O_2

A freshly prepared CD_3CN solution of **1** (3mM) and 2,3-dimethyl-2-butene (90 mM) in a NMR tube under aerobic conditions (air, 1 atm) was submitted to irradiation at 630 nm during 30 min. The NMR spectra of the solution before and after irradiation were recorded. As seen on Figure ESI, the final solution contains 2,3-dimethylbut-3-en-2-ylhydroperoxid and **2** in its non-oxygenated form ie. the endo-peroxide 2O2 was not formed. The two olefin proton signals for trapped hydroperoxide appear in the open window of 4.88 - 4.93 ppm.

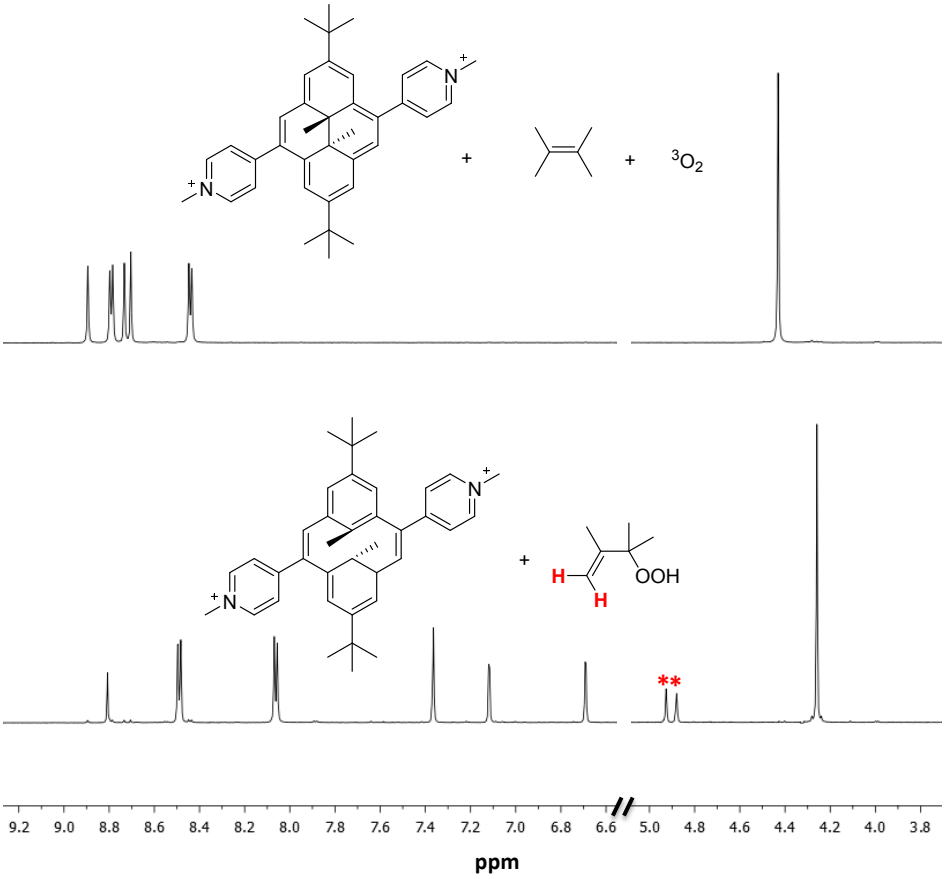


Figure S7. ^{1}H NMR spectra of : (A) **1** in presence of 30-fold excess of 2,3-dimethyl-2-butene and air, (B) Photogenerated **2** and hydroxoperoxide. Signals (*) at 4.88 and 4.93 ppm correspond to the two olefin protons for trapped product.

10. Evidence of singlet oxygen production by trapping ESR experiments.

Singlet oxygen trapping experiments were carried out by ESR using 2,2,6,6-tetramethyl-4-piperidone, TEMPD.[3] A solution of **1** (44μM) with TEMPD (1M) in CH_3CN was irradiated (λ>630nm) and converted into **2-O_2**. ESR spectra were recorded before and after irradiation process. The sample was then heated in the dark to release singlet oxygen.

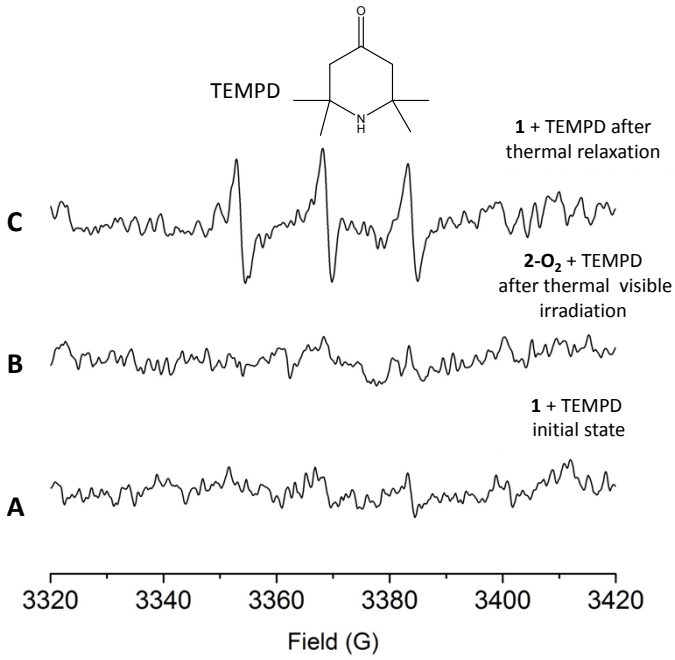


Figure S8. EPR spectra of nitroxide radical generated from TEMPD. 1M solution of TEMPD was mixed with 44μM of **1**. **A**: initial state. **B**: upon irradiation with red light (λ>630nm). C: upon thermal relaxation and recovery of **1**.

11. Crystal data

Table S1. Crystal Data and Structure Refinement for **2** and **2-O_2**.

Formula	$C_{50}H_{70}F_{12}N_4O_{2.93}P_2$
Fw (g mol^{-1})	1063.90
Crystal system	monoclinic
Space group	P 21/c
a (Å)	15.137(3)
b (Å)	14.675(3)
c (Å)	13.735(3)
α (deg.)	90.00
β (deg.)	114.58(3)
γ(deg.)	90.00
V (Å^3) / Z	2774.5(9) / 2
Dx (g cm^{-3})	1.273
μ (cm^{-1})	1.61
Crystal dim. (mm)	0.32x0.28x0.17
T (K)	200
θ range for coll. (deg.)	1 – 27.52
nb. of rflns. coll.	42954
Data/restraints/parameters	6362/221/425
R (*I*) [a]all/R[I>2σ(I)]	11.95% / 7.62%
Goodness of fit S	1.051
$\Delta\rho_{min}/\Delta\rho_{max}$ (e Å^{-3})	-0.512 / 0.774

[a] $R = \sum||I_o| - |I_c||/\sum|I_o|$.

12. Reférences

[1] Roldan, D.; Cobo, S.; Lafolet, F.; Vilà, N.; Bochot, C.; Bucher, C.; Saint-Aman, E.; Boggio-Pasqua, M.; Garavelli, M.; Royal, G. *Chem. Eur. J.* **2015**, *21*, 455-467.

[2] (a) Mitchell, R. H.; Ward, T. R.; Chen, Y.; Wang, Y.; Weerawarna, S. A.; Dibble, P. W.; Marsella, M. J.; Almutairi, A.; Wang, Z.-Q. *J. Am. Chem. Soc.* **2003**, *125*, 2974-2988. (b) Vilà, N.; Royal, G.; Loiseau, F.; Deronzier, A. *Inorg. Chem.* **2011**, *50*, 10581-10591.

[3] Hideg, É.; Deák, Z.; Hakala-Yatkin, M.; Karonen, M.; Rutherford, A. W.; Tyystjärvi, E.; Vass, I.; Krieger-Liszkay, A. *Biochim. Biophys. Acta* **2011**, *1807*, 1658-1661