Electronic Supplementary Information

Understanding and Controlling the Efficiency of Au₂₄M(SR)₁₈

Nanoclusters as Singlet-Oxygen Photosensitizers

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Table of Contents

- 1. Chemicals
- 2. Determination of Relevant Kinetic and Thermodynamic Parameters
- 3. Table S1
- 4. Supplemental Experimental Procedures
- 5. Figures S1-S9
- 6. References

1. Chemicals. HAuCl₄·3H₂O (Aldrich, 99.9%), Hg(NO₃)₂ (Sigma-Aldrich, \geq 99.99%), Cd(NO₃)₂ (Carlo Erba Reagents, 99%), tetra-*n*-octylammonium bromide (Aldrich, 98%), *n*-propanethiol (Aldrich, 99%), *n*-butanethiol (Aldrich, 99%), phenylethanethiol (Aldrich, \geq 99%), NaBH₄ (Aldrich, 99%), tetrahydrofuran (THF, Sigma-Aldrich, 99.9%), toluene (Sigma-Aldrich, 99.7%), diethyl ether (Sigma-Aldrich, 99.8%), methanol (Aldrich, 99.8%), triethylamine (Sigma-Aldrich, \geq 99%), 2,2,6,6-tetramethyl-4-oxo-1-piperidinyloxy (TEMPONE, Aldrich), 9,10-diphenylanthracene (DPA, Alfa Aesar, 99%), *meso*-tetraphenylporphyrin (TPP, Sigma-Aldrich \geq 99%, were used as received. For electrochemistry, dichloromethane (DCM anhydrous, Sigma-Aldrich, \geq 99.8%) was stored under an argon atmosphere. Tetra-*n*-butylammonium hexafluorophosphate (Fluka, 99%) was recrystallized from ethanol. Low conductivity water was milliQ Water pro

analysis (Merck). Column chromatography was carried out using silica gel from Macherey-Nagel (MN-Kieselgel 60 M, 230-400 mesh).

2. Determination of Relevant Kinetic and Thermodynamic Parameters.

Diffusion Rate and Equilibrium Constants. The diffusion rate constant k_d is calculated with the Smoluchowski equation, $k_d = 4\pi N_A (D_O + D_M) (r_O + r_M)$, where N_A is the Avogadro number, and r_O and r_M are the radii of O₂ (1.72 Å)^{S1} and Au₂₅(SC4)₁₈⁻ (9.4 Å).^{S2} As to the diffusion coefficients, D_O can be estimated from a correlation with the solvent viscosity η , $D = (2.6 \times 10^{-7})\eta^{-2/3}$,^{S3} use of 1.39 centipoise for the toluene's viscosity at 240 K^{S4} yields $D_O = 2.1 \times 10^{-5}$ cm² s⁻¹. For the much larger cluster, the use of the Stokes-Einstein equation ($D = k_B T/6\pi\eta r_M$, where k_B is the Boltzmann constant) is licit and yields $D_M = 1.35 \times 10^{-6}$ cm² s⁻¹. Hence, $k_d = 1.9 \times 10^{10}$ M⁻¹ s⁻¹. The equilibrium constant for cage formation (K_d) can be calculated according to the Debye equation, ^{S5,S6} which for the specific case is $K_d = 4\pi N_A (r_O + r_M)^2 \delta r/1000$. By using for δr the typical value of ~1 Å, ^{S7} K_d and k_{-d} are calculated to be 0.94 M⁻¹ and 2 x 10¹⁰ s⁻¹, respectively.

Preexponential Factor in eq. 14. The frequency factor Z in eq. 14 is estimated by taking into account the role of solvent friction in determining the rate of crossing the barrier:⁵⁸

(S1)
$$Z = \frac{1}{\tau_L} \left(\frac{\Delta G_{0 ET}^{\neq}}{4\pi RT} \right)^{\frac{1}{2}} \quad \tau_L = \frac{\varepsilon_{\infty}}{\varepsilon_S} \tau_D \quad \tau_D = \frac{4\pi \eta r^3}{k_B T}$$

where, $\tau_{\rm L}$ is the longitudinal relaxation time, $\tau_{\rm D}$ is the Debye relaxation, and $\varepsilon_{\rm s}$ and ε_{∞} are the static and high-frequency permittivities. For toluene at 240 K, $\tau_{\rm L}$ can be estimated from the linear temperature dependence of the two permittivities;^{S9} the molecular radius of toluene, *r*, is 2.75 Å.^{S10}

Determination of the Intrinsic Barrier (eq. 16). The kinetic analysis requires a good estimate of the charge-transfer intrinsic barrier $\Delta G_0^{\neq}_{\text{ET}}$, as defined in eq S2 (eq 16 in the main text):

(S2)
$$\Delta G_0^{\neq}_{\text{ET}} = [(\Delta G_0^{\neq}_{\text{ET}})_{\text{hom},\text{ex},\text{M} + /\text{M}} + (\Delta G_0^{\neq}_{\text{ET}})_{\text{hom},\text{ex},\text{O2/O2-}}]/2$$

The two $(\Delta G_0^{\neq}_{\text{ET}})_{\text{hom,ex}}$ values are estimated from the corresponding heterogeneous intrinsic barriers through eq S3 (eq 17 in main text):^{S11}

(S3)
$$(\Delta G_0^{\neq})_{\text{hom,ex}} = 2(\Delta G_0^{\neq})_{\text{het}} - (\Delta G_{0,s}^{\neq})_{\text{hom,ex}}$$

where $(\Delta G_{0,s}^{\neq})_{\text{hom,ex}}$ is the homogeneous solvent reorganization term. For the cluster, we use the electrochemical $(\Delta G_0^{\neq}_{\rm ET})_{\rm het} = 0.222$ eV, which was obtained in DCM/0.1 M TBAH, at 298 K from the standard heterogeneous rate constant, ^{S12} using $k^{\circ}_{het} = Z_{el} \exp[(\Delta G_0^{\neq}_{\text{ET}})_{\text{het}}/RT$ with $Z_{\text{el}} = (RT/2\pi M)^{1/2}$ (M = molar mass). For ${}^{1}\text{O}_2/\text{O}_2^{-\bullet}$ and assuming that the intrinsic barriers of ${}^{1}O_{2}/O_{2}^{-}$ and ${}^{3}O_{2}/O_{2}^{-}$ are the same, we obtain $(\Delta G_{0}^{\neq}E_{T})_{het} = 0.408$ eV by cyclic-voltammetry analysis of the oxygen reduction peak. The solvent intrinsic barrier $\Delta G_{0,s}^{\neq}$ ET depends on both solvent and temperature through the Pekar factor, ε_{op}^{-1} - $\varepsilon_{\rm s}^{-1}$, where $\varepsilon_{\rm op}$ is the optical (usually taken as n^2 , where n = refractive index) dielectric constant, whereas the inner component $\Delta G_{0,i}^{\neq}$ can be considered as essentially independent. The solvent intrinsic barriers can be obtained from the empirical equation $(\Delta G_{0,s}^{\neq}_{\text{ET}})_{\text{het}} = 0.604/r$ (were r is the molecular radius in Å).^{S11} $(\Delta G_{0,i}^{\neq}_{\text{ET}})_{\text{het}}$ is obtained as $(\Delta G_0^{\neq}_{\text{ET}})_{\text{het}}$ - $(\Delta G_{0,s}^{\neq}_{\text{ET}})_{\text{het}}$. For both species, we use a heuristic approach in which $(\Delta G_0^{\neq}_{\rm ET})_{\rm het}$ is transformed into a toluene/240 K intrinsic barrier by using the same $(\Delta G_{0,i}^{\neq}{}_{ET})_{het}$ value and the $(\Delta G_{0,s}^{\neq}{}_{ET})_{het}$ corrected for the ratio between the appropriate Pekar factors (using the temperature dependence of ε_{op} and ε_s in toluene). Use of $(\Delta G_{0,s}^{\neq})_{\text{hom,ex}} = (\Delta G_{0,s}^{\neq}_{\text{ET}})_{\text{het}}^{\text{S13}}$ in eq S3 and then use of eq S2 yields for the $^{1}O_{2}/Au_{25}(SC4)_{18}$ system a value of $\Delta G_{0}^{\neq}E_{T} = 0.23$ eV. For DCM at 298 K, $\Delta G_{0}^{\neq}E_{T}$ is much larger, 0.40 eV (value obtained using a $(\Delta G_0^{\neq}_{ET})_{het}$ vs $(\Delta G_0^{\neq})_{hom.ex}$ correlation valid for more polar solvents).^{S11}

Determination of the Reaction Free Energy ΔG°_{ET} . Eq 18 (or its equivalent form including the Coulombic term) provides a reasonable estimate of ΔG°_{ET} : using the powerful phase-modulated voltammetry technique,^{S14} Jones and Fox^{S15} found that the

actual excited-state redox potentials are roughly consistent with the estimates from the Rehm-Weller approach. In the present case, the excited species, ${}^{1}O_{2}$, is the same for all clusters and thus any minor error would be systematic. $E^{\circ}({}^{1}O_{2}/O_{2}^{-})$ will thus be taken as $E^{\circ}(O_2/O_2^{-1}) - E_{exc}/F = -0.850 + 0.974 = 0.124 \text{ V} (DCM/0.1 \text{ M TBAH})$. The E° values of the clusters refer to DCM, whose dielectric constant ($\varepsilon_s = 9.1$, or 12.5 if the presence of the supporting electrolyte is included)^{S2} is not much larger than that of toluene ($\varepsilon_s = 2.4$). This is a mild approximation, especially if one considers that these calculations are generally performed using E° values obtained in polar solvents,^{S1} especially acetonitrile ($\varepsilon_s = 37.5$), which introduces a quite severe approximation when used for describing processes carried out in low-polarity solvents. It should be also noted that due to the presence of the permeable monolayer protecting the cluster,^{S12} the effective dielectric constant (ε_{eff}) experienced by the gold core and the nearby oxygen molecule is (i) smaller than that of DCM (for SC3, we estimated $\varepsilon_{eff} = 7.7$)^{S2} and, for the same reason, (ii) slightly larger than that of toluene, 2.4, as the ligands provide a intrinsic contribution to $\varepsilon_{\rm eff}$ of 3-3.6.^{S2} This kind of nanoenvironment is obviously not present in common sensitizers.

		Au ₂₅ (SC4) ₁₈	$Au_{24}Cd(SC2Ph)_{18}^{0}$
$E^{\circ}(\mathbf{V})$	Formal potential	-0.188	0.430
k_{Δ} (s ⁻¹)	Experimental decay rate constant	3.69 x 10 ⁵	$3.58 \ge 10^4$
$k_{\rm q} ({\rm M}^{-1}{\rm s}^{-1})$	Quenching rate constant (eq 6)	$3.40 \ge 10^8$	6.90 x 10 ⁶
$k_{\rm d} ({\rm M}^{-1} {\rm s}^{-1})$	Diffusion rate constant	1.9 x 10 ¹⁰	$2.5 \ge 10^{10}$
$K_{\rm d} \left({\rm M}^{-1} \right)$	Equilibrium constant for cage formation	0.94	1.69
$k_{\rm CT}$ (s ⁻¹)	Rate constant for CT in reaction 8	1.8 x 10 ¹⁰	1.4x 10 ⁹
k- _{CT} (s ⁻¹)	Rate constant for the backward CT in reaction 8	8.7 x 10 ⁸	$1.2 \ge 10^{10}$
$k_{\rm ISC} (s^{-1})$	Rate constant for ISC in reaction 9	1.8×10^7	$3.7 \ge 10^7$
$k_{\text{PET}}(s^{-1})$	Rate constant for ET in reaction 10	3.9×10^8	$3.2 \ge 10^6$
k-PET (s ⁻¹)	Rate constant for the backward ET in reaction 10	1.1×10^2	5.2×10^4
k- _{ET} (s ⁻¹)	Rate constant for the ET in reaction 11	2.0 x 10 ¹⁰	1.3×10^{10}
$k_{\rm ET}$ (s ⁻¹)	Rate constant for the backward ET in reaction 11	2.5 x 10 ⁻⁴	1.7 x 10 ⁻¹⁷

3. Table S1. Summary of Kinetic and Thermodynamic Parameters.

4. Supplemental Experimental Procedures. The syntheses of the undoped and doped clusters were carried out as described previously.^{S16-S20}

For the CWEPR measurements, we used a continuous wave Bruker ER200D Xband spectrometer. The spectra were recorded with 100 KHz field modulation, 2 mW microwave power, 0.10 mT modulation amplitude, 10.24 ms time constant, and 81.92 ms conversion time. The sample solutions were placed in a 4 mm outer-diameter (o.d.) quartz tube. To remove oxygen from the samples, the solutions were carefully degassed by several freeze-pump-thaw cycles, and sealed under vacuum conditions (10^{-3} Torr).

The inversion recovery EPR experiments were performed using a pulsed Bruker ER580 X-band spectrometer. The solutions of the samples were placed in 3 mm o.d.

quartz tubes. A two-pulse inversion recovery pulse sequence was used. In this experiment the direction of the net magnetization of TEMPONE is initially switched by a π pulse from +z to -z. After a variable delay time t, a $\pi/2$ pulse brings the magnetization to the xy plane and a free induction decay (FID) signal is detected. By plotting the FID amplitude vs t, one obtains the inversion recovery curve, which represents the recovery of the inverted z component of the magnetization to the thermal equilibrium. The initial time interval t between the first π pulse and second $\pi/2$ pulse was 200 ns. The $\pi/2$ pulse length of 32 ns was chosen to avoid spin diffusion phenomena, after checking that the recovery curves did not change by further increasing the pulse length. The field value was set at the maximum of the central hyperfine line of the integrated CWEPR spectrum of TEMPONE (corresponding to the 0 value in the first derivative spectrum). The inversion recovery curve was obtained plotting the area of the FID vs the time interval. We recorded 1024 points corresponding to different t values, with a time step Δt of 4 ns. 300 FIDs were recorded and averaged for each t value. A time delay of 1500 μ s was set between each pulse sequence to allow the full recovery of magnetization. To obtain the T1 value, a single exponential function was fit to the FID amplitude vs. t curves.

The UV-vis absorption spectra of the clusters were obtained in toluene with a Thermo Scientific Evolution 60S spectrophotometer. The spectra were recorded with a spectral resolution of 0.5 nm. The samples were either diluted to 0.2 mM (photostability experiments related to the TREPR experimental conditions) or used as such (0.13 mM, excitation/emission experiments) in 1 mm cuvettes. The extent of oxidation was determined through analysis of the derivative UV-vis spectrum at 390 nm.^{S21}

Emission spectra were recorded at room temperature in aerated toluene solutions in 1-mm quartz cuvettes with a FluoroMax-3 spectrofluorimeter (HORIBA). A front-face configuration (tilted angle of 60°) was used to acquire the emission spectra and an average of three independent measurements was performed for each sample. The concentration of $Au_{25}(SC4)_{18}^{-}$ and $Au_{24}Cd(SC4)_{18}^{0}$ was adjusted by using the absorbance spectrum and the pertinent molar extinction coefficient, that is, 4.58 x 10⁴ M⁻¹ cm⁻¹ (398 nm) and 4.68 x 10⁴ M⁻¹ cm⁻¹ (401 nm) respectively. Each experiment was carried out by using a freshly prepared 300 μ l toluene solution of 1 mM nanocluster and 0.01 mM DPA in a 3 mm o.d., 2 mm inner diameter EPR glass tube. The sample was cooled to 240 K and irradiated with the Nd:YAG laser used for the TREPR experiments at a wavelength of 532 nm for 10 min. The solution was let to reach room temperature and was then diluted (30 μ l in 200 μ l toluene) in a 1 mm optical-path length quartz cuvette before recording the absorption, emission and excitation spectra. Dilution was meant to minimize the inner filter effects due to the strong absorbance of the nanoclusters in the same optical region of the DPA emission, i.e., 400–500 nm. The optical measurements were recorded 30 min after the laser irradiation.

5. Figures S1-S9.



Figure S1. Determination of T2 from the reciprocal of the full-width-at-half-height (FWHH) of the integral of the CWEPR spectrum. The central line of the CWEPR spectrum of TEMPONE (top) is analyzed by transforming the experimental line (a) into its integral (b). The full-width-at-half-height is obtained by simulating the peak as a Lorentzian curve.



Figure S2. TREPR transient of the emission-polarized signal (average of the three signals) observed for 1 mM $Au_{25}(SC3)_{18}^{-}$ and 0.5 mM TEMPONE in toluene under anaerobic conditions (black), with monoexponential fit to the data (red).



Figure S3. UV–Vis absorption spectra of $Au_{25}(SC4)_{18}^{-1}$ in toluene in the presence of TEMPONE (1:0.5) before irradiation (black) and after 2 h irradiation (red). The blue trace shows the spectrum of pure $Au_{25}(SC4)_{18}^{0}$. The irradiation was carried out on a 1 mM $Au_{25}(SC4)_{18}^{-1}$ solution, whereas for obtaining the optical spectra the samples were diluted to 0.2 mM. 1 mm quartz cuvette, room temperature. The spectra were normalized to obtain A = 1 at 400 nm. The extent of oxidation, 8.8%, was calculated by using the absorbance derivative at 390 nm, according to a method previously developed.^{S21}



Figure S4. TREPR transient of the emission-polarized signal (average of the three signals) observed for 1 mM $Au_{24}Cd(SC4)_{18}^{0}$ and 0.5 mM TEMPONE in toluene under anaerobic conditions (black), with monoexponential fit to the data (red).



Figure S5. TREPR transient of the emission-polarized signal (average of the three signals) observed for 1 mM $Au_{24}Cd(SC2Ph)_{18}^{0}$ and 0.5 mM TEMPONE in toluene under anaerobic conditions (black), with monoexponential fit to the data (red).



Figure S6. Excitation Spectra ($\lambda_{exc} = 450 \text{ nm}$) of a toluene solution of 1.3 x 10⁻³ mM DPA and 0.13 mM Au₂₄Cd(SC4)₁₈⁰ before (black trace) and after (red trace) 10 min irradiation at 532 nm at 240 K. The spectra were obtained at room temperature with a 1 mm path length cuvette in a front-face configuration.



Figure S7. Excitation Spectra ($\lambda_{exc} = 450 \text{ nm}$) of a toluene solution of 1.3 x 10⁻³ mM DPA and 0.13 mM Au₂₅(SC4)₁₈⁻ before (black trace) and after (red trace) 10 min irradiation at 532 nm at 240 K. The spectra were obtained at room temperature with a 1 mm path length cuvette in a front-face configuration.



Figure S8. Absorption spectra of a toluene solution of 1.3×10^{-3} mM DPA and 0.13 mM Au₂₄Cd(SC4)₁₈⁰ before (black trace) and after (red trace) 10 min irradiation at 532 nm at 240 K. The spectra were obtained at room temperature with a 1 mm cuvette.



Figure S9. Absorption spectra of a toluene solution of 1.3×10^{-3} mM DPA and 0.13 mM Au₂₅(SC4)₁₈⁻ before (black trace) and after (red trace) 10 min irradiation at 532 nm at 240 K. The spectra were obtained at room temperature a 1 mm cuvette.

6. References

- S1. C. Schweitzer and R. Schmidt, Chem. Rev., 2003, 103, 1685–1757.
- S2. S. Antonello, T. Dainese, M. De Nardi, L. Perotti and F. Maran, *ChemElectroChem*, 2016, **3**, 1237–1244.
- S3. A. Schumpe and P. Lühring, J. Chem. Eng. Data, 1990, 35, 24-25.
- S4. F. J. V.Santos, C. A. Nieto de Castro, J. H. Dymond, N. K. Dalaouti, M. J. Assael and A. Nagashima, J. Phys. Chem. Ref. Data, 2006, 35, 1-8.
- S5. P. Debye, J. Electrochem. Soc., 1942, 82, 265-272.
- S6. N. Sutin, Progr. Inorg. Chem., 1983, **30**, 441-498.
- S7. R. A. Marcus and N. Sutin, *Biochim. Biophys. Acta*, 1985, 811, 265-322.
- S8. L. D. Zusman, Chem. Phys., 1980, 49, 295-304.
- S9. W. F. Hassel and S. Walker, *Trans. Farad. Soc.*, 1966, **62**, 861-873.

- S10. D. E. O'Reilley and E. M. Peterson, J. Chem. Phys., 1972, 56, 2262-2266.
- S11. A. M. Meneses, S. Antonello, M.-C. Arévalo, C. C. González, J. Sharma, A. N. Wallette, M. S. Workentin and F. Maran, *Chem. Eur. J.*, 2007, 13, 7983-7995.
- S12. S. Antonello, G. Arrigoni, T. Dainese, M. De Nardi, G. Parisio, L. Perotti, A. René, A. Venzo and F. Maran, ACS Nano, 2014, 8, 2788–2795.
- S13. N. S. Hush, *Electrochim. Acta*, 1968, **13**, 1005–1023.
- S14. D. D. M. Wayner, D. J. McPhee and D. Griller, J. Am. Chem. Soc., 1988, 110, 132-137.
- S15. W. E. Jones, Jr. and M. A. Fox, J. Phys. Chem., 1994, 98, 5095-5099.
- S16. W. Fei, S. Antonello, T. Dainese, A. Dolmella, M. Lahtinen, K. Rissanen, A. Venzo and F. Maran, J. Am. Chem. Soc., 2019, 141, 16033-16045.
- S17. M. De Nardi, S. Antonello, D. Jiang, F. Pan, K. Rissanen, M. Ruzzi, A. Venzo, A. Zoleo and F. Maran, ACS Nano, 2014, 8, 8505-8512.
- S19. M. Agrachev, S. Antonello, T. Dainese, J. A. Gascón, F. Pan, K. Rissanen, M. Ruzzi, A. Venzo, A. Zoleo and F. Maran, *Chem. Sci.*, 2016, 7, 6910-6918.
- S20. S. Antonello, T. Dainese, F. Pan, K. Rissanen and F. Maran, J. Am. Chem. Soc., 2017, 139, 4168–4174.
- S21. A. Venzo, S. Antonello, J. A. Gascón, I. Guryanov, R. D. Leapman, N. V. Perera, A. Sousa, M. Zamuner, A. Zanella and F. Maran, *Anal. Chem.*, 2011, 83, 6355– 6362.