D. Wöhrle, Universität Bremen

The Excited State of Phthalocyanines - A Field of a Many Applications

Beginning 1989

Makromol. Chem. **190**, *961 – 974 (1989)*

Phthalocyanines on mineral carriers, 4[a)]

Low-molecular-weight and polymeric phthalocyanines on SiO_2, γ-Al_2O_3 and active charcoal as catalysts for the oxidation of 2-mercaptoethanol

Dieter Wöhrle, Thomas Buck, Uwe Hündorf*

Institut für Organische und Makromolekulare Chemie, Universität Bremen, Leobenerstr. NW2, 2800 Bremen 33, F.R.G.

Günter Schulz-Ekloff

Institut für Angewandte und Physikalische Chemie, Universität Bremen, Leobenerstr. NW2, 2800 Bremen 33, F.R.G.

Atanas Andreev

Institute of Kinetics and Catalysis, Bulgarian Academy of Sciences, Sofia 1040, Bulgaria

(Date of receipt: September 7, 1988)

SUMMARY:

Low-molecular-weight phthalocyaninatocobalt compounds **2a – d** and polymeric phthalocyaninatocobalt derivatives **4**, **6a**, **b** were prepared on the surface of the inorganic carriers SiO_2 or γ-Al_2O_3 and of active charcoal, the range of loading being 11,9 – 0,2 wt.-%. The oxidation of 2-mercaptoethanol in an aqueous solution at pH 9 was used as a model reaction for demercaptizations of petroleum fractions with phthalocyanines on carriers as heterogeneous catalysts. The catalytic activity, related to the phthalocyanine content, was found to increase with increasing dispersion of the complex on the carrier. The influence of the type of support on the activity is given by the following order: SiO_2 < γ-Al_2O_3 < Norit charcoal. Polymeric phthalocyanines exhibit a higher catalytic activity as compared with low-molecular-weight phthalocyanines. The mechanism of the oxidation of the thiol is discussed.

J. Photochem. Photobiol. B: Biol., *21* (1993) 155–165

Liposome-delivered Zn(II)-2,3-naphthalocyanines as potential sensitizers for PDT: synthesis, photochemical, pharmacokinetic and phototherapeutic studies

D. Wöhrle[a,†], M. Shopova[b], S. Müller[a], A.D. Milev[c], V.N. Mantareva[b] and K.K. Krastev[b]
[a]*Institut für Organische und Makromolekulare Chemie, Universität Bremen, 2800 Bremen 33 (Germany)*
[b]*Institute of Organic Chemistry, Bulgarian Academy of Sciences, 1113 Sofia (Bulgaria)*
[c]*National Oncology Center, 1157 Sofia (Bulgaria)*

(Received March 19, 1993; accepted July 26, 1993)

Abstract

The aim of this investigation is to report the synthesis and fundamental photochemical properties of naphthalocyanines with potential interest for photodynamic therapy (PDT), as well as their pharmacokinetics and phototherapeutic effects in a tumor model. Four zinc naphthalocyanines (ZnNc), unsubstituted ZnNc **1**, tetraacetylamido-substituted ZnNc **2**, tetraamino-substituted ZnNc **3** and tetramethoxy-substituted ZnNc **4** absorbing around 760–770 nm, were synthesized. The dye-sensitized photo-oxidation of 1,3-diphenylisobenzofuran via $^1O_2$ was studied in dimethylsulfoxide (DMSO). Quantum yields for this photoreaction are 0.135–0.164 and are relatively independent of the kind of substituent. In addition, the photoinduced electron transfer studied in *N,N*-dimethylformamide–water in the presence of methylviologen and mercaptoethanol is only slightly influenced by the kind of substituent. The pharmacokinetic properties of ZnNc **1** in hamsters bearing a transplanted rhabdomyosarcoma were studied using dipalmitoylphosphatidylcholine liposomes. Experimental PDT of rhabdomyosarcoma was carried out using liposome-delivered ZnNc **1–4**. The phototherapeutic effect was evaluated by tumor photonecrosis, the mean tumor diameter during the observation period and the percentage of cured animals. The best effect was found after PDT with ZnNc **2** (50% of the treated animals were cured). A slightly lower effect was observed after application of ZnNc **4** (40% cured animals). No effect at all was noted after PDT with ZnNc **3** and a very low efficiency was found after treatment with ZnNc **1** as photosensitizer. Obviously, the photodynamic effect depends on the biological characteristics as well as on the nature of the substituents.

Today

Photodynamic inactivation of *Aeromonas hydrophila* by cationic phthalocyanines with different hydrophobicity

Veselin Kussovski[a], Vanya Mantareva[b], Ivan Angelov[b], Petya Orozova[a], Dieter Wöhrle[c], Günter Schnurpfeil[c], Ekaterina Borisova[d] & Latchezar Avramov[d]

[a]The Stephan Angeloff Institute of Microbiology, Bulgarian Academy of Sciences,, Bl. 26, 1113 Sofia, Bulgaria;
[b]Institute of Organic Chemistry, Bulgarian Academy of Sciences, Acad. G. Bonchev, str., Bl. 9, 1113 Sofia, Bulgaria;
[c]Institute of Organic and Macromolecular Chemistry, University of Bremen, 330 440, 28334 Bremen, Germany;
[d]Institute of Electronics, Bulgarian Academy of Sciences 72, Tsarigradsko chaussee Blvd., 1784 Sofia,

Abstract

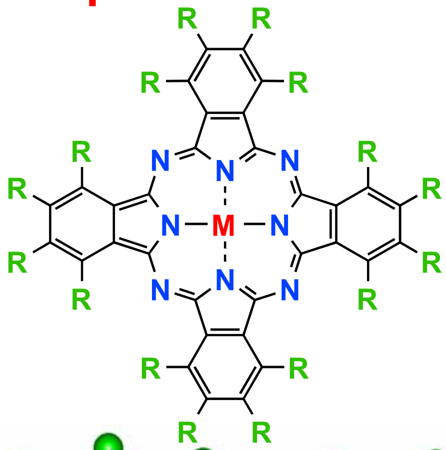
The gram-negative *Aeromonas hydrophila* were photodynamically treated with four cationic phthalocyanines substituted with *pyridyloxy*-substituents with increasing hydrocarbon chain. The different hydrophobic nature of the studied phthalocyanines was irrelevant towards the uptake behavior of aeromonads cells. An obvious inverse dependence of the drug uptake on the cell density was observed. The optimal combination of gentle treatment conditions such as low drug concentration and mild irradiation parameters was established for photoinactivation of aeromonads.

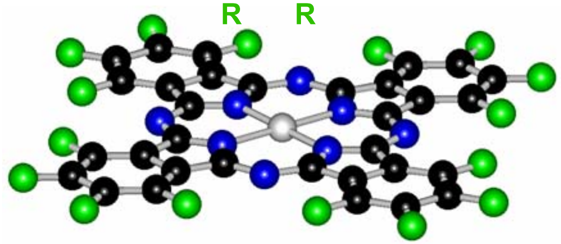
D. Wöhrle, Universität Bremen

The Excited State of Phthalocyanines - A Field of a Many Applications

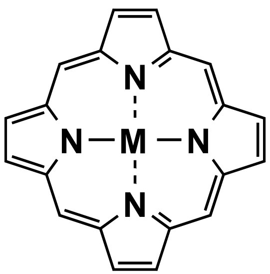
1. Introduction

Absorption at ~675 nm

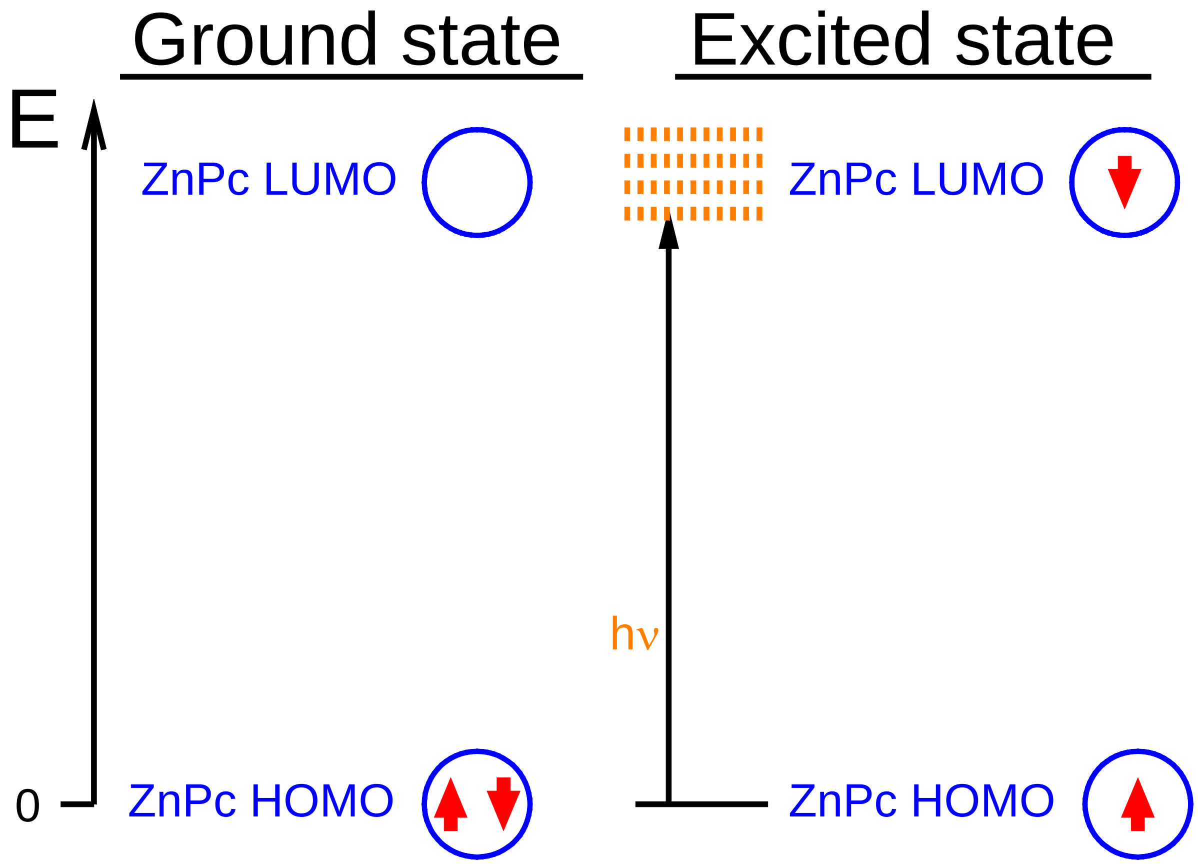




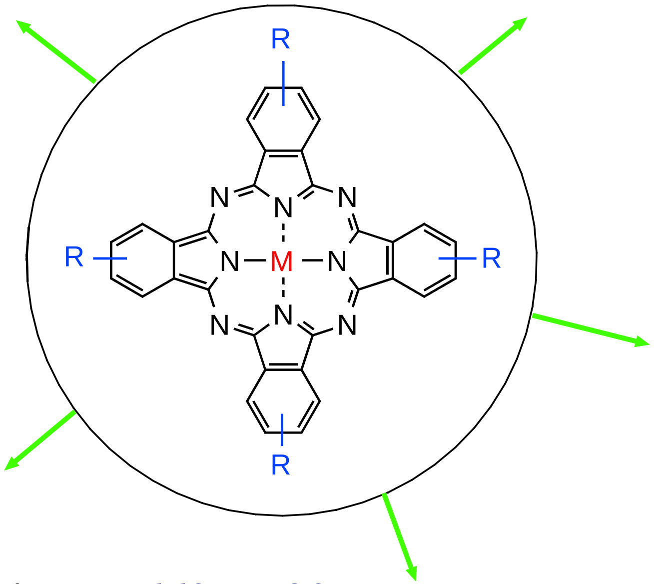
porphin



What happens after absorption of light From/by excited states of phthalocyanines??



Phthalocyanines (Pc): A system with Broad Applications



Absorption at 660 – 730 nm

Applications

- Production per year more than 100.000 tons
- Broad use as pigments and dyes
- Ti(IV)(O) phthalocyanine as photoconductor in laser printers and copy machines
- Active material in CD-R
- Cu(II)Pc in LC displays
- Co(II) phthalocyanines as catalyst for the petroleum sweetening (MEROX process)
- Al(III) and Zn(II) phthalocyanines as photosensitizers in the photodynamic cancer therapy
- Photocatalyst (solar photochemistry)

Much more applications of phthalocyanines compared to porphyrins.

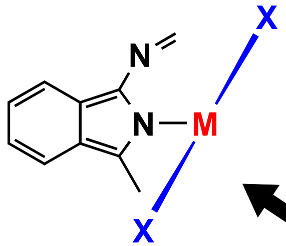
Phthalocyanines much less expensive then porphyrins

Interest for applications

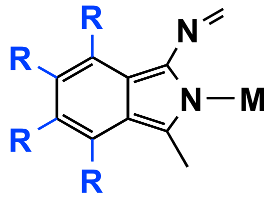
- Optical properties e.g. NLO
- Organic conductors
- Organic photovoltaic cells
- etc.

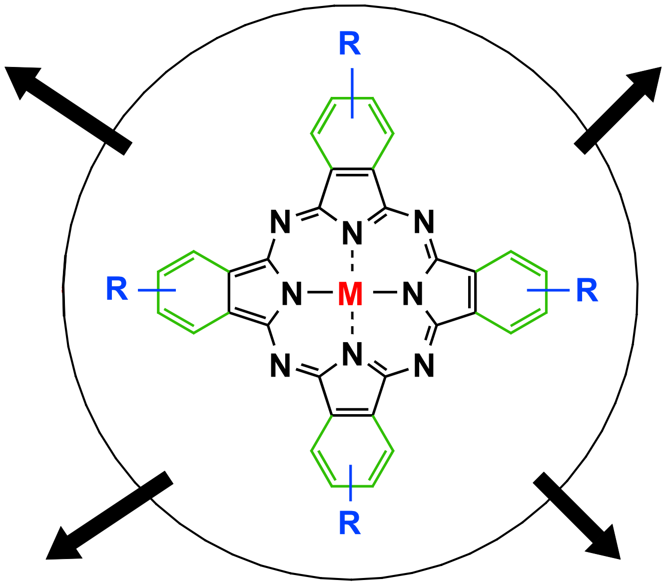
Phthalocyanines (Pc): A system with great variability

Variation of the metal ion:

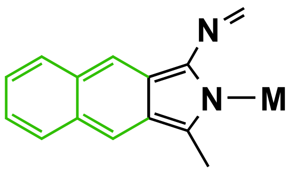


Variation of 1-16 substituents:

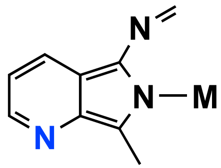


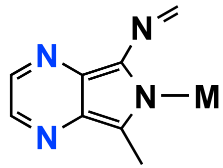


Variation of annelation:



Varition of hetero-atoms:
-pyrido - pyrazino

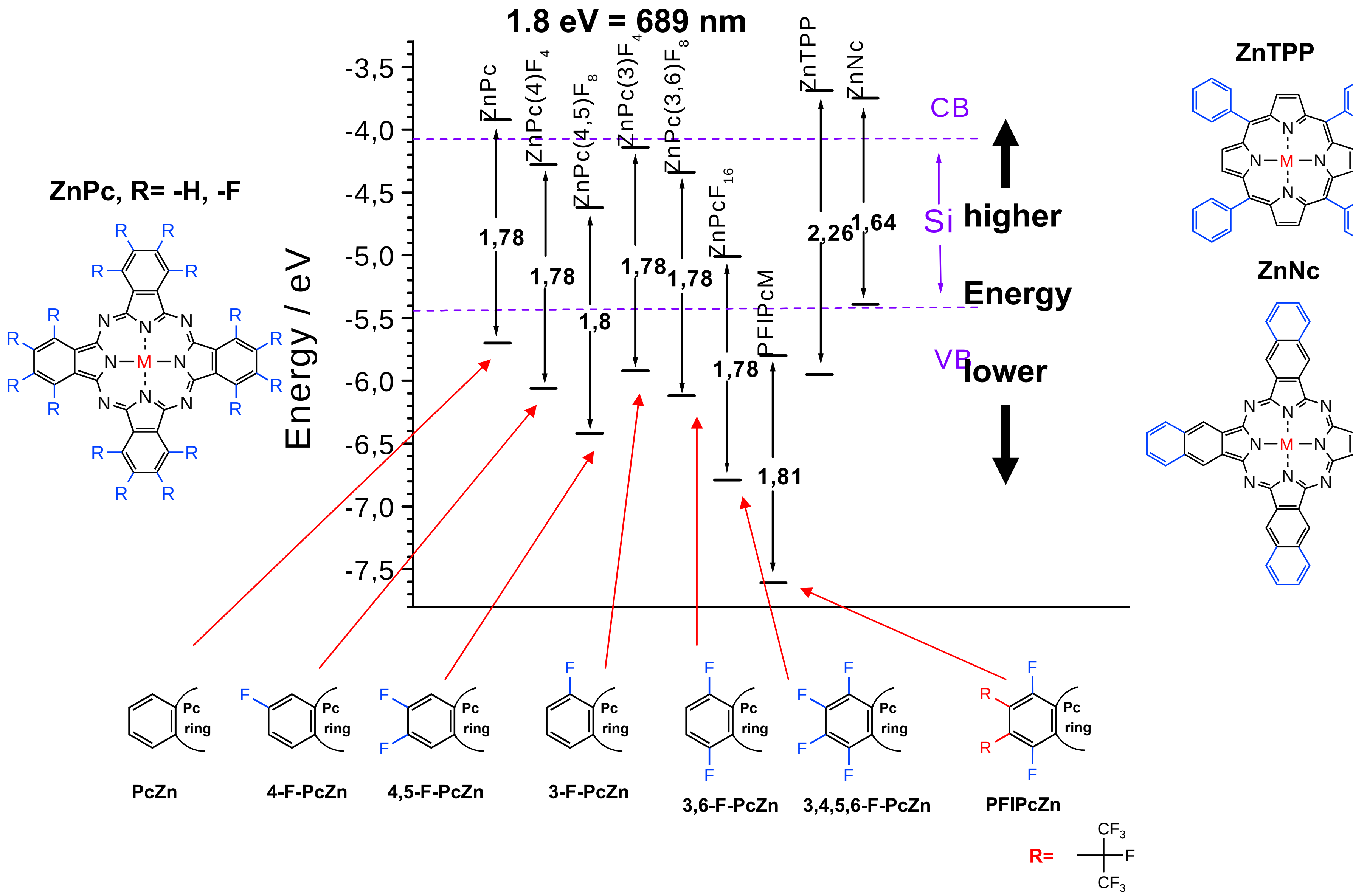




Combination with inorganic and organic macromolecules

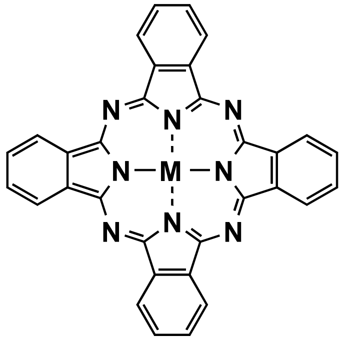
Position of HOMO/LUMO energy positions

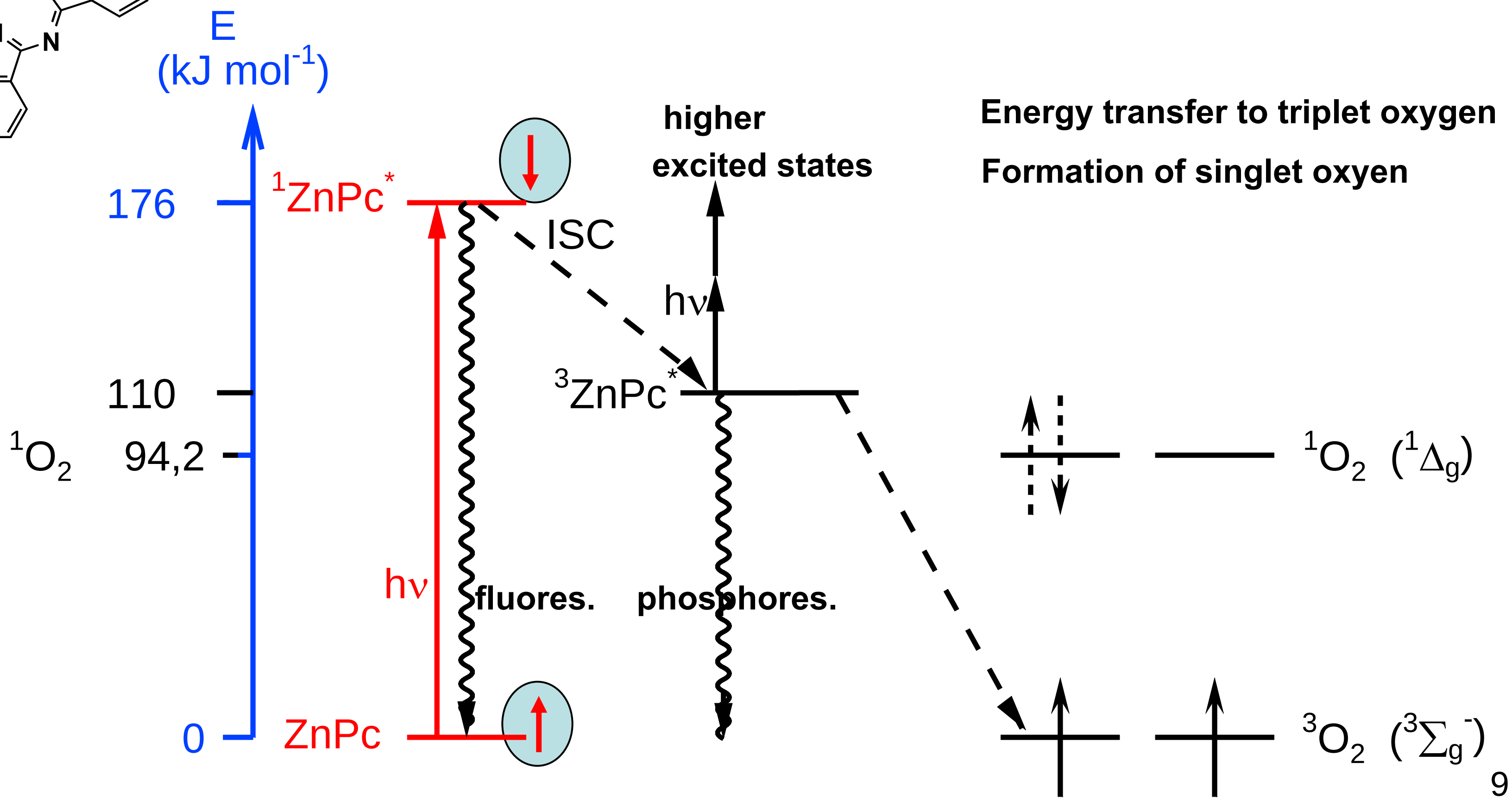
Programme: Hyperchem, Release 4.5,PM3 method, gradient 10exp-3, next lowest RHF



2. Excited singlet state
Position of HOMO/LUMO and absorption of phthalocyanines,

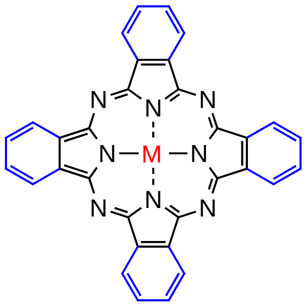
Absorption of Zn(II) phthalocyanine at ~672 nm (E= 176 kJ mol^{-1}, 1.84 eV).
Lifetime excited singlet state: ~3.8 ns.



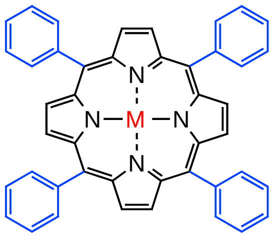


Visible light absorption in solution

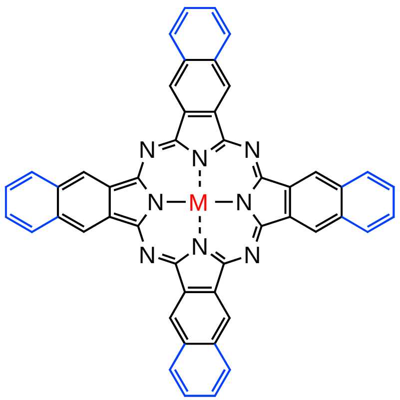
ZnPc

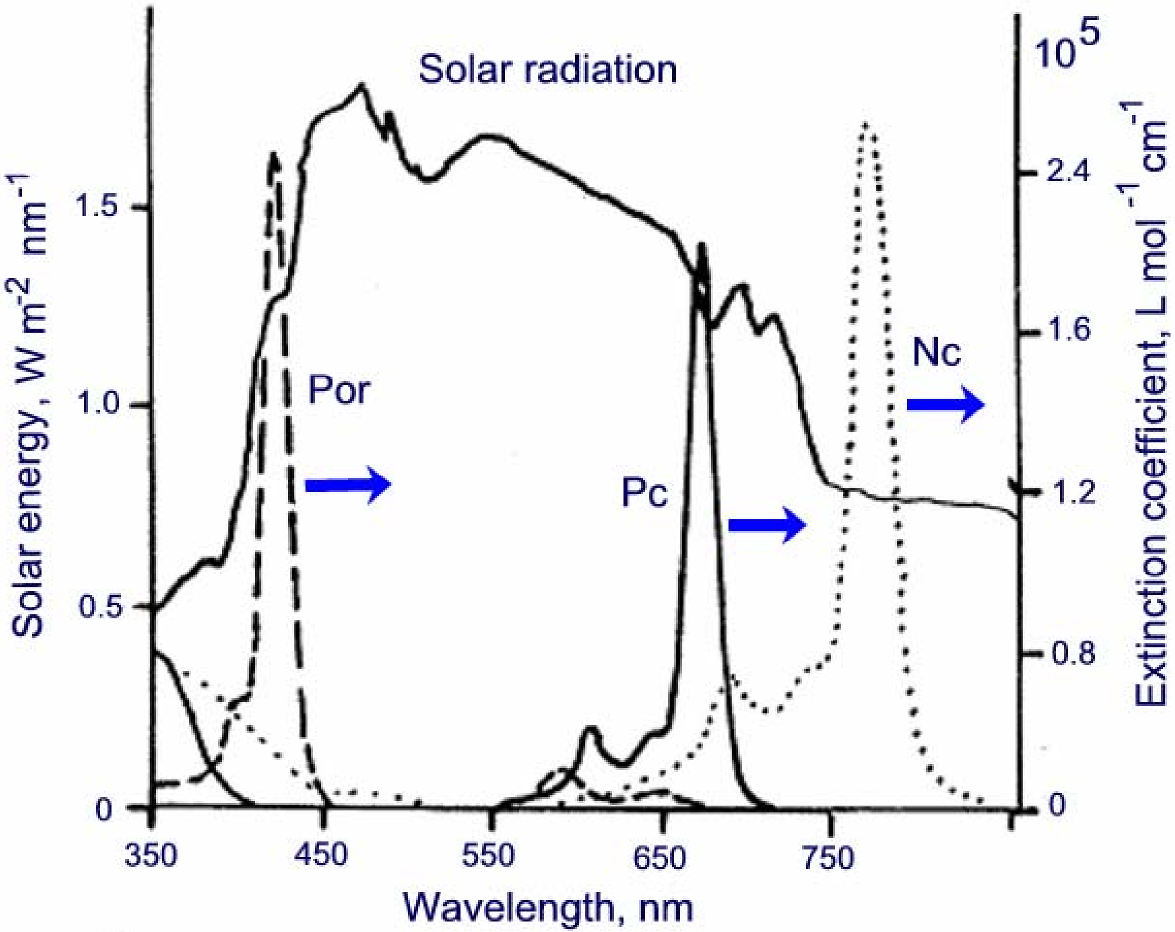


ZnTPP



ZnNc



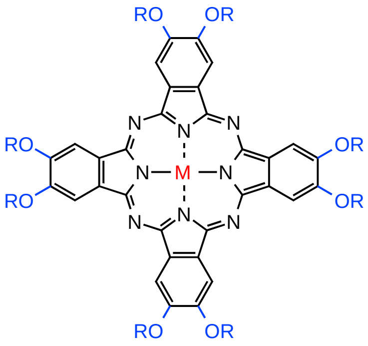


Novel NIR-Absorbing Annulated Multinuclear Phthalocyanines

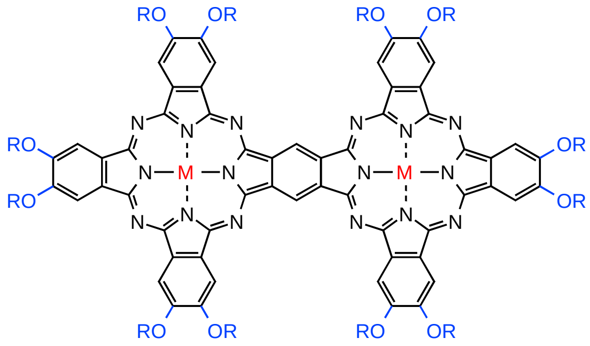
D. Wöhrle, S. Makarov, *Bremen; 2007/8*

O.Suvorova, S. Makarov, *Nizhnii Novgorod, Russia*

B. Roeder, C. Litwinski, E.A. Ermilov, *Berlin*

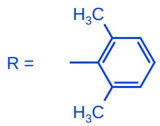


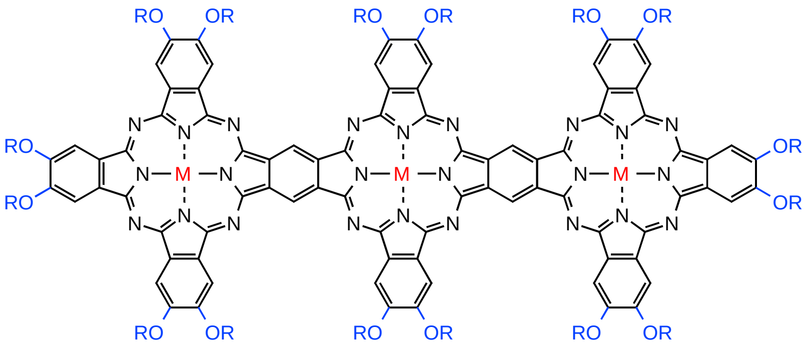
M **20-25%**



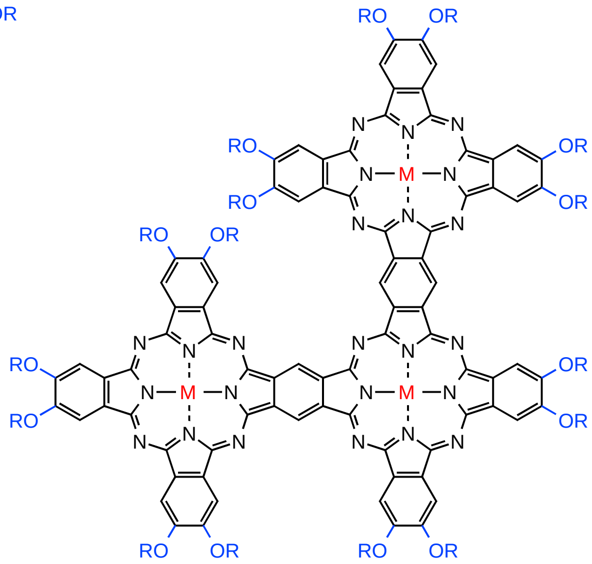
M M **8-11%**

M = 2H(I), Zn(II), Co(II)



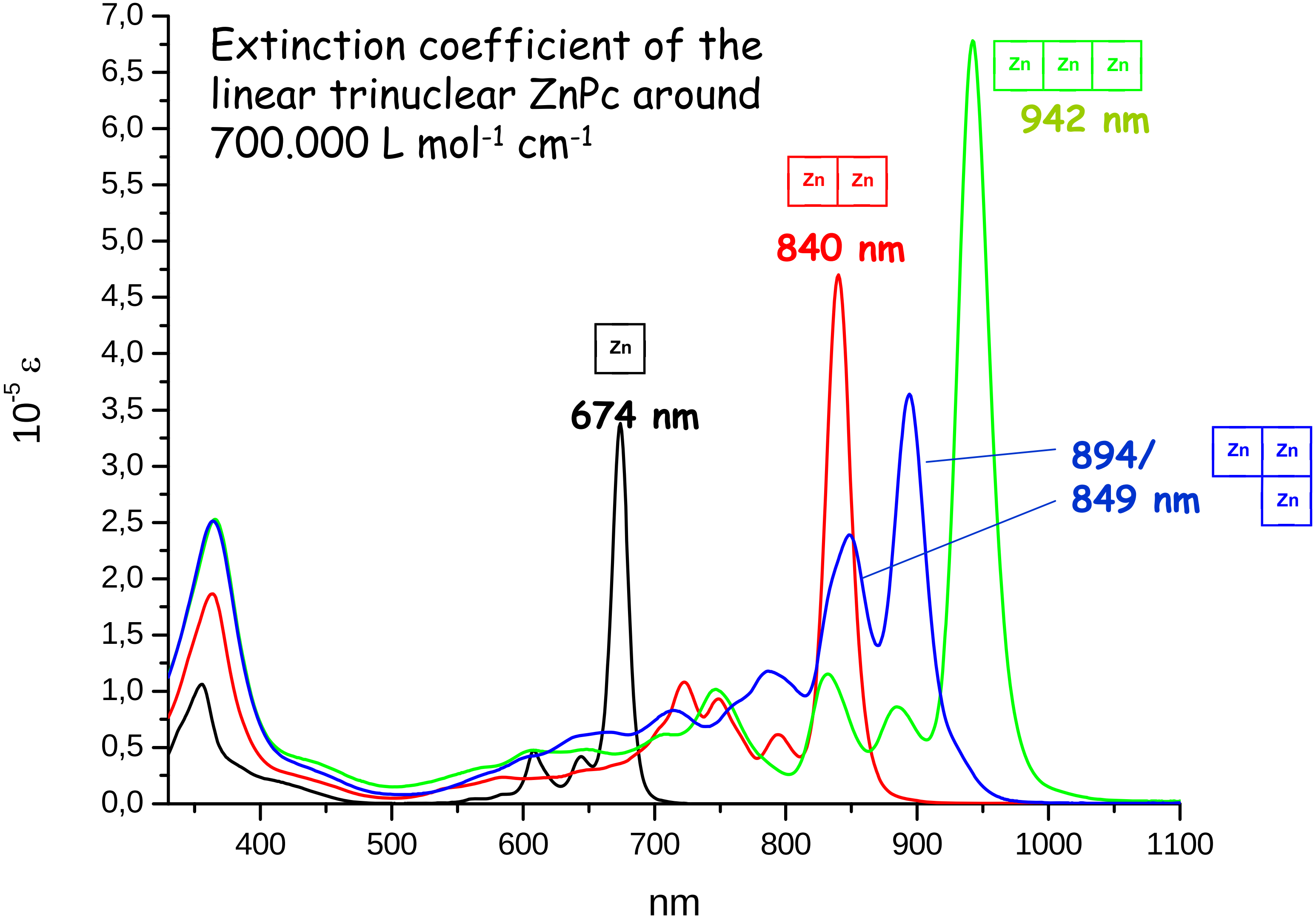


M M M **0.7-0.9%**



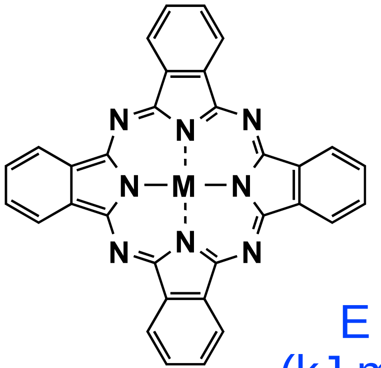
M
M M **1.5-1.7%**

Electronic absorption spectra of ZnPcs in THF



Possible applications: NIR sensors, organic photovoltaic cells

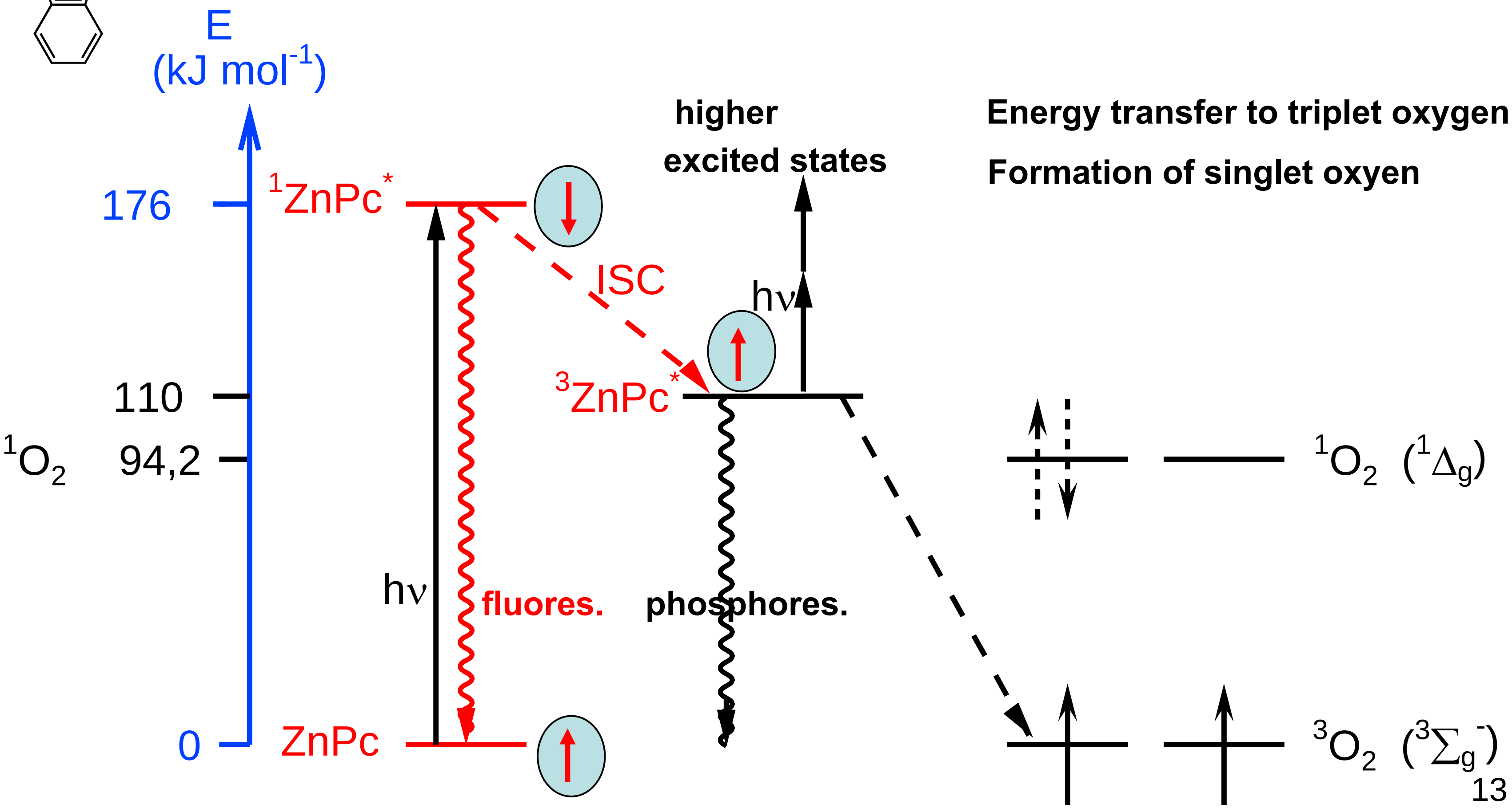
3. Fluorescence and intersystem crossing of phthalocyanines



Zn(II) phthalocyanine life time of excited singlet state: ~3.8 ns.

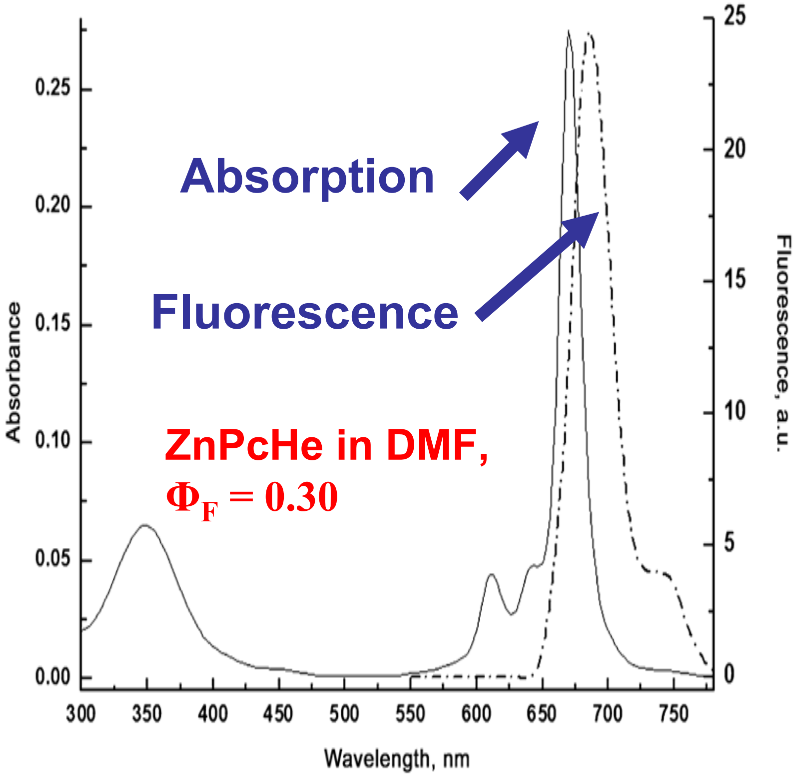
Quantum yield of intersystem crossing (ISC): ~0.65 (65%).

Florescence at ~679 nm. Fluorescence quantum yield: ~0.3 (30%).

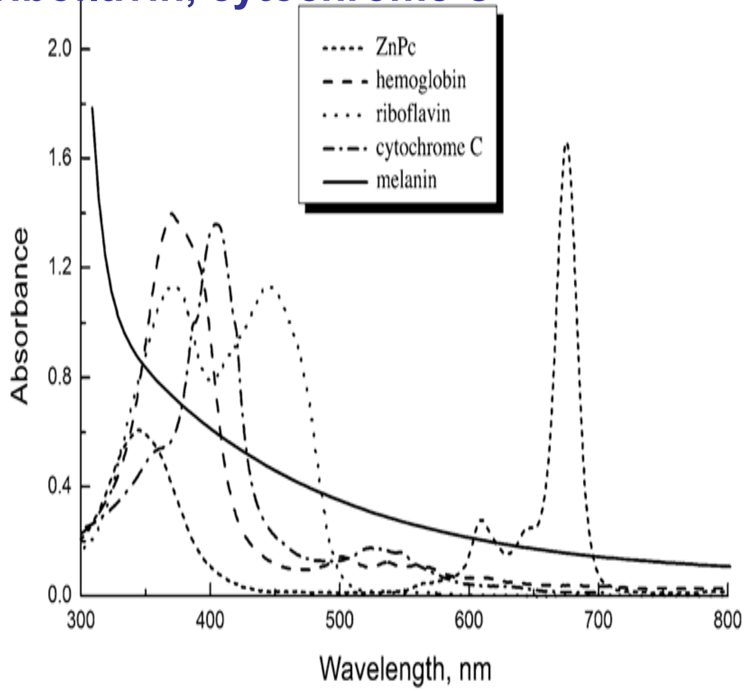


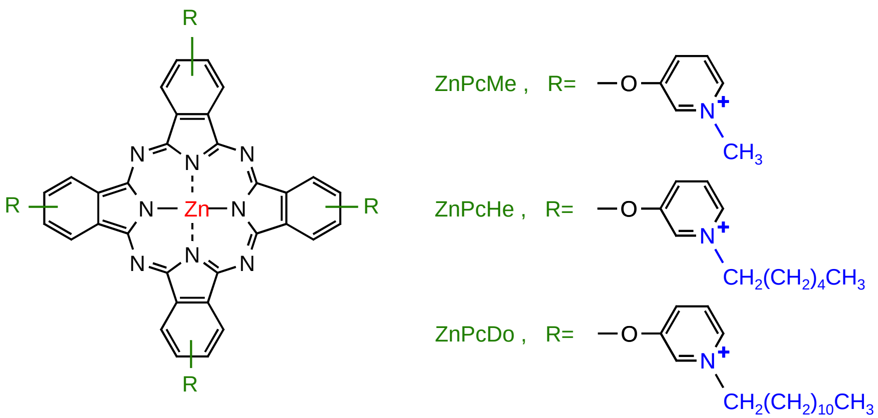
Long wavelength absorbing cationic Zn(II)-phthalocyanines as fluorescent contrast agents for B16 pigmented Melanoma

V.Mantareva, M.Peeva, et al;; 2005



Absorption spectrum of ZnPcHe
in comparison to melanin, hemoglobin, riboflavin, cytochrome C





27.2%

53.1%

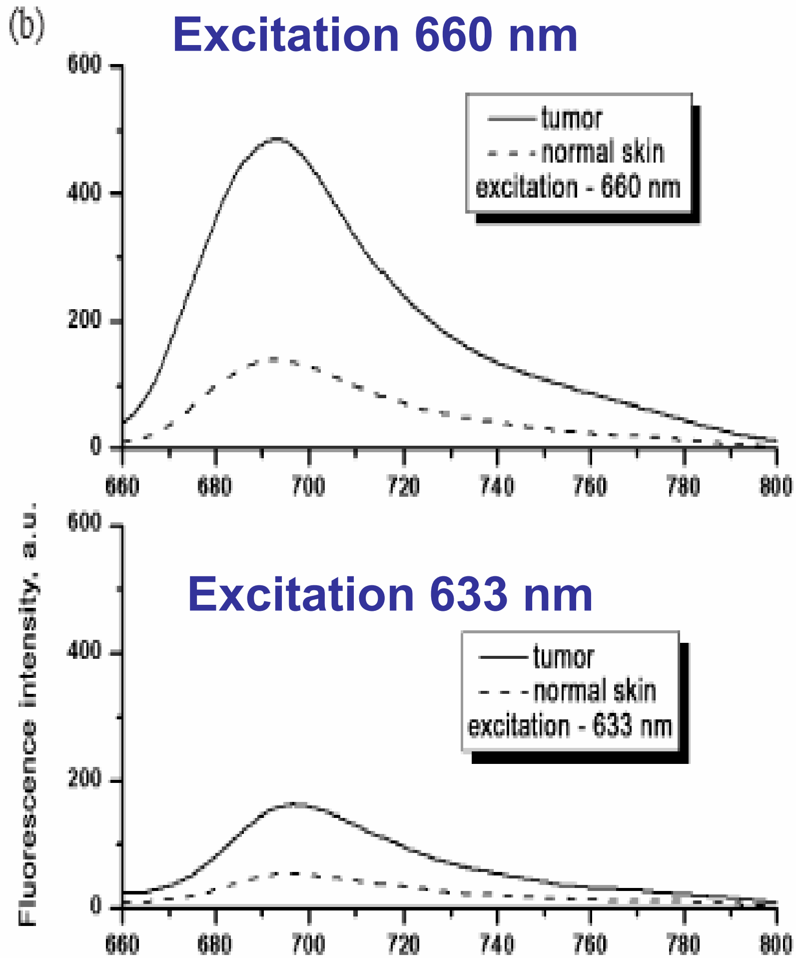
21.2%

Uptake of ZnPcs in pigmented melanoma tumour cells measured 90 min after incubation of $2x10^{-9}$ mol/mL

In vivo fluorescence spectra of tumour and healthy tissue

B16 pigmented melanoma in mice,
spectra recorded 24 after i.p. injection of ZnPcHe in DPPC liposomes, 0.3 mg/kg
Irradiation by optical fibre system

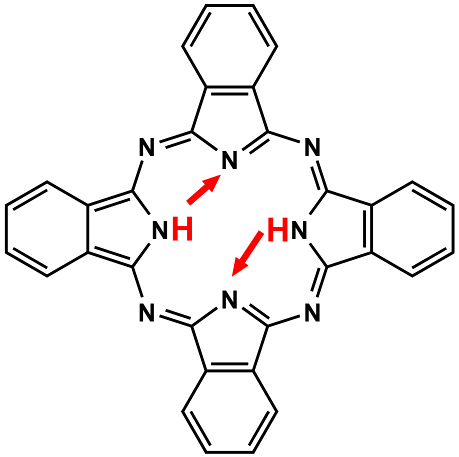
Tumor and surrounded normal skin

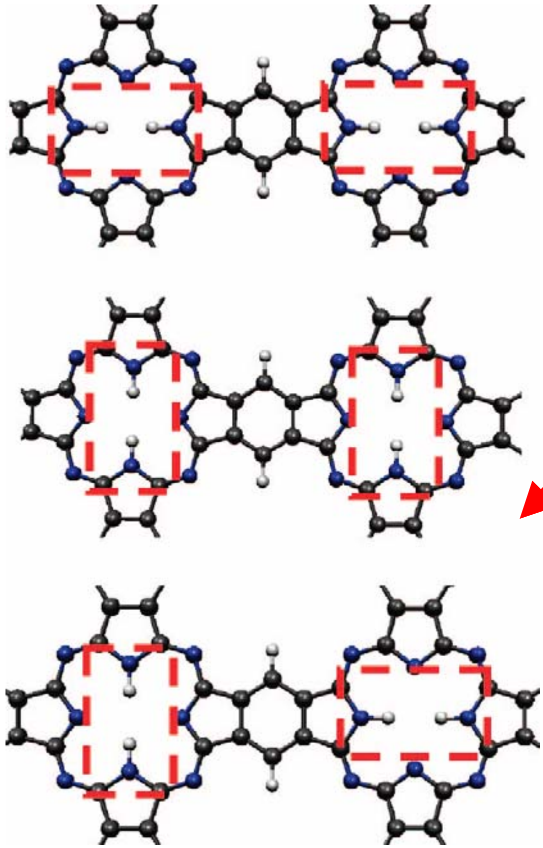


Fluorescence intensity ratio
Timour : normal skin = ~3

Clinically used ALA (aminolaevulinic acid) has fluorescence intensity ratio tumour : normal 2 times less

Tautomers in metal-free binuclear H_2Pc-H_2Pc
at Room Temp. for the first time



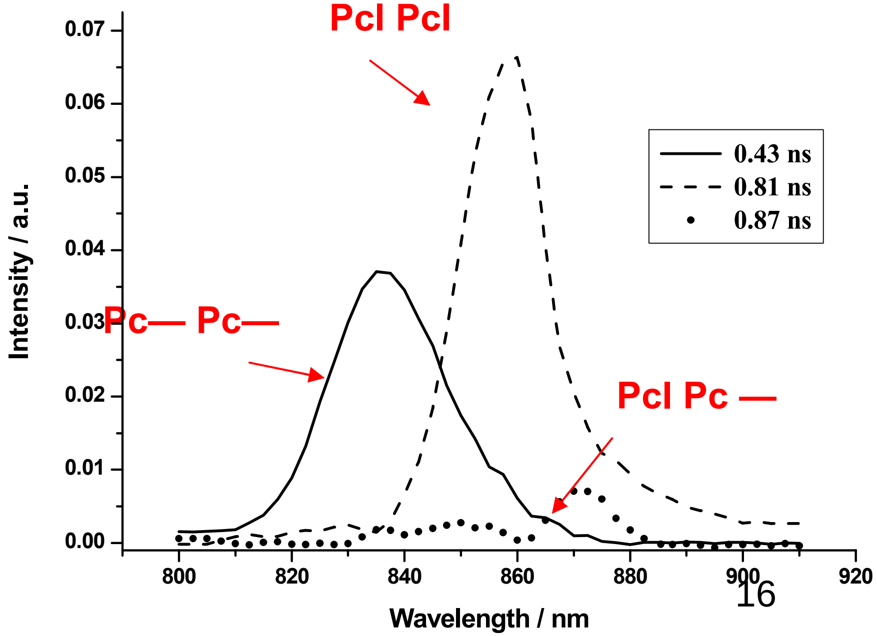


Pc— Pc— parallel to bonding axis

PcI PcI perpendicular to bonding axis

PcI Pc — mixed to bonding axis

Fluorescence spectra at Room Temp.

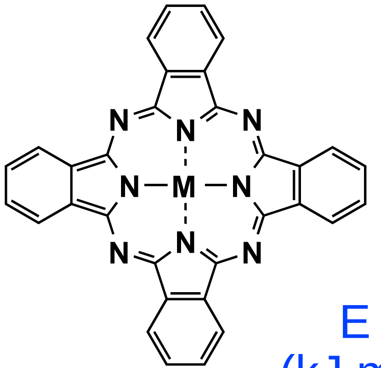


Up to now different tautomers of metal-free porphyrins and phthalocyanines were observed at T lower -180 °C

Potential application for molecular information storage

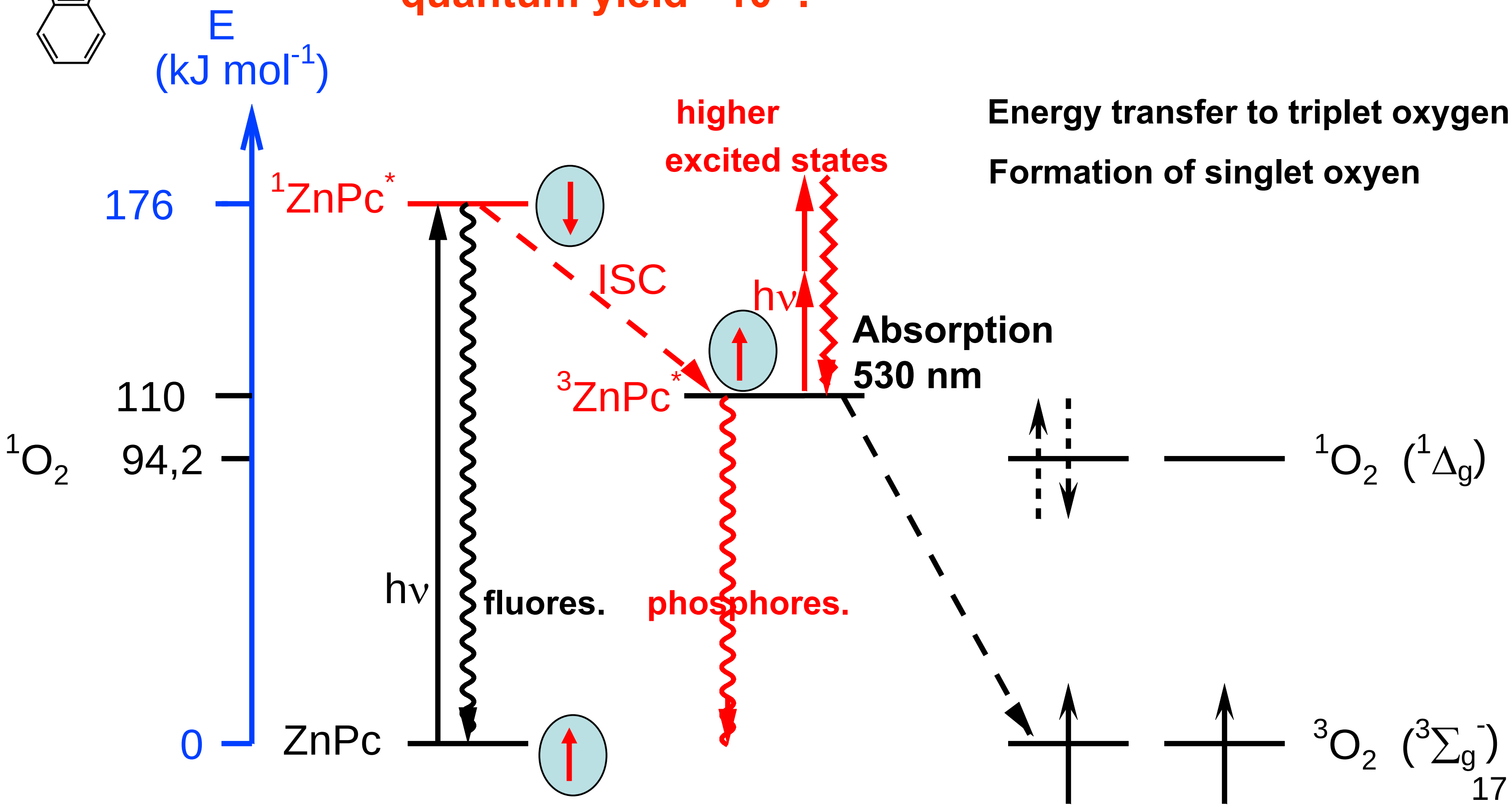
4. Higher excited triplet state

Nonlinear optical property: Optical limiting by phthalocyanines



Zn(II) phthalocyanine excited triplet state quantum yield ~0.65 (65%), life time ~1 ms.

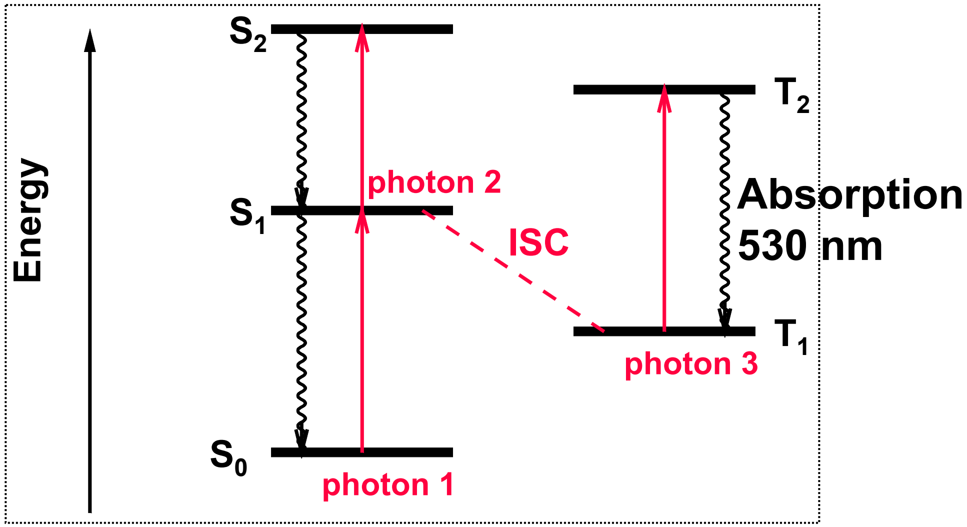
Phosporescence at ~1100nm. Phophorescence quantum yield ~10^{-5}.



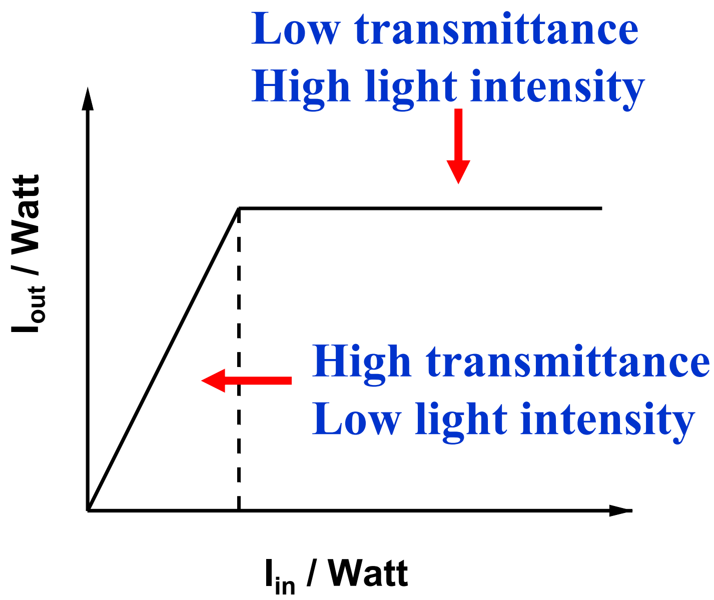
Higher excited triplet state
Nonlinear optical property: Optical limiting by phthalocyanines
For use as filters (light protection)

A. *Slodek, Bremen; 2006*
B. *W. Blau et al., Dublin*

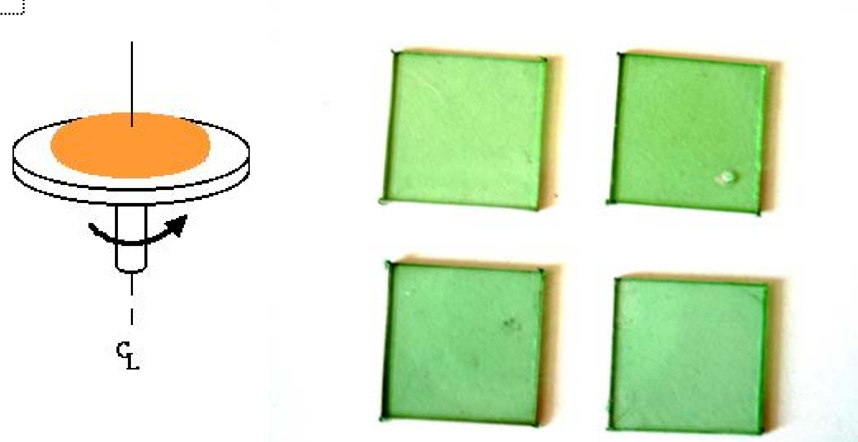
Five-level scheme for excitation



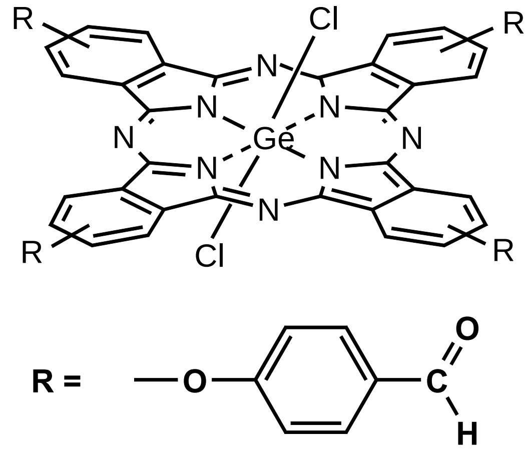
Saturable absorption



Solids devices of phthalocyanines
by spin-coating
on glas or sapphire in
poly(methylmethacrylate)

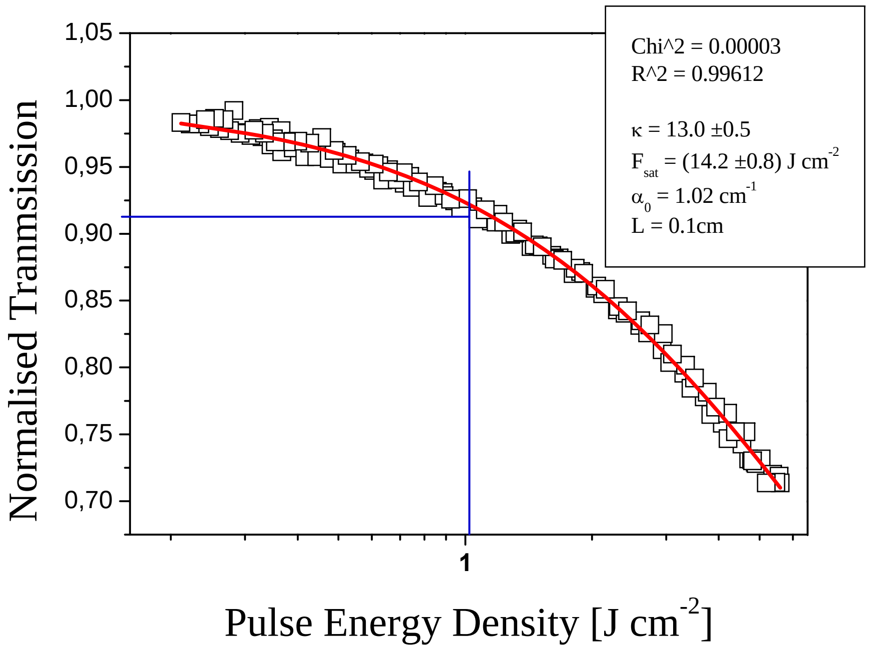


Optical limiting
fitted for nonlinear absorption coefficient

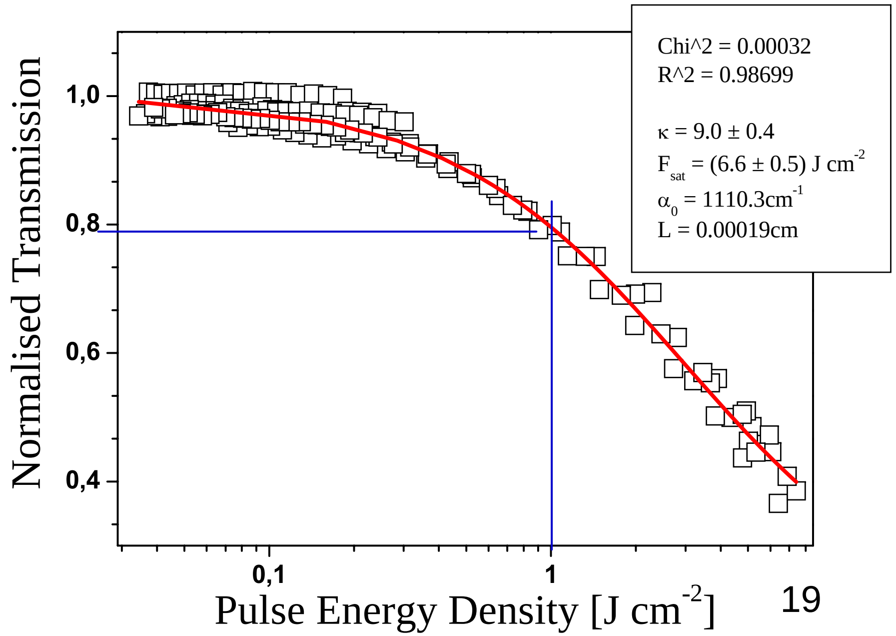


Irradiation by 6 ns 532 nm laser light pulses
From a Q switched frequency doubled Nd:YAG laser,
Pulse rate 10 Hz

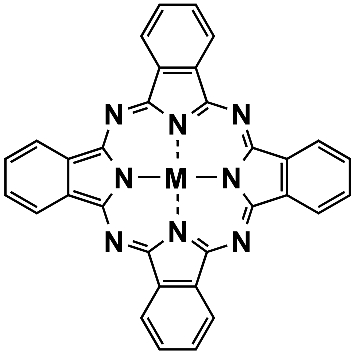
Measured in THF solution



Measured as thin film of 2 µm Poly(methylmethacrylate) on glass

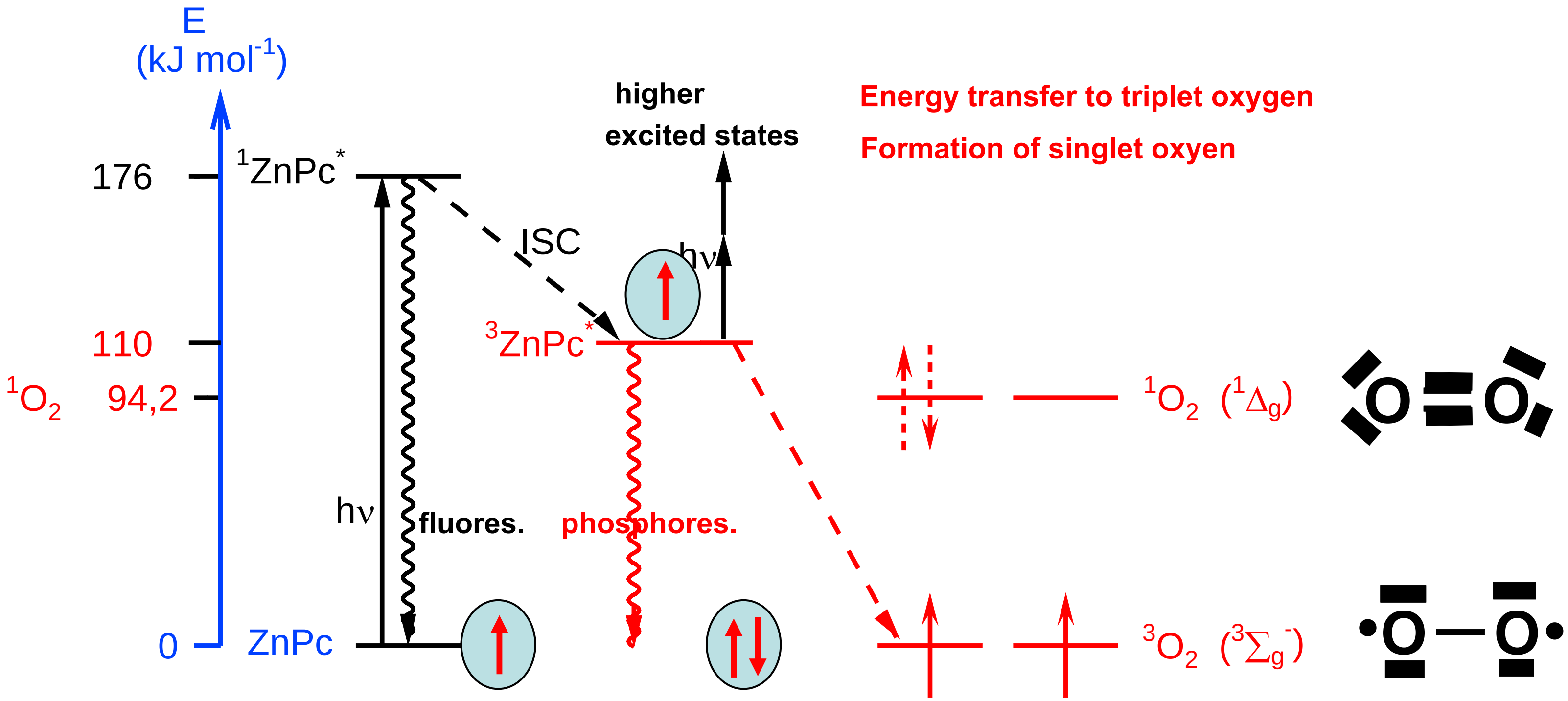


5. Excited triplet state of phthalocyanines
Energy transfer to triplet oxygen



Zn(II) phthalocyanine excited triplet state quantum yield ~0.65 (65%), life time ~1 ms.

Energy transfer to triplet oxygen under formation of singlet Oxygen: Quantum yield ~0.55 (55%).



First:

Pc ⟶ $^1Pc^*$ ⟶ $^3Pc^*$

Second:

$^3Pc^*$ + $^3O_2$ ⟶ Pc + $^1O_2$

Third:

$^1O_2$ +substrate ⟶ oxidized substrate

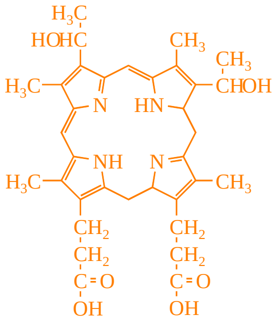
5a. Phthalocyanines and Naphthalocyanines for photodynamic cancer therapy

M. Shopova, V. Mantereva, M. Peeva, et al; 1993-2001

hematoporphyrin

λ 610 -635 nm

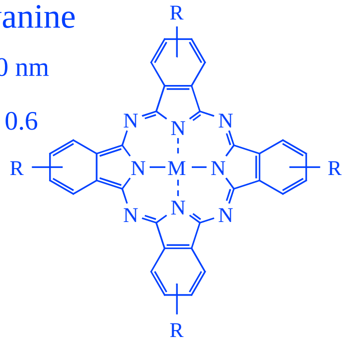
ϕ $^1O_2$ 0.6 - 0.7



phthalocyanine

λ 660 - 730 nm

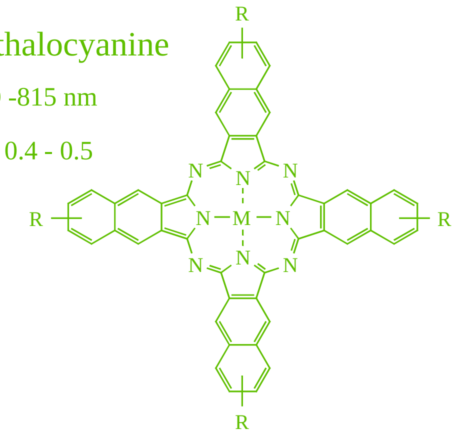
ϕ $^1O_2$ 0.5 - 0.6

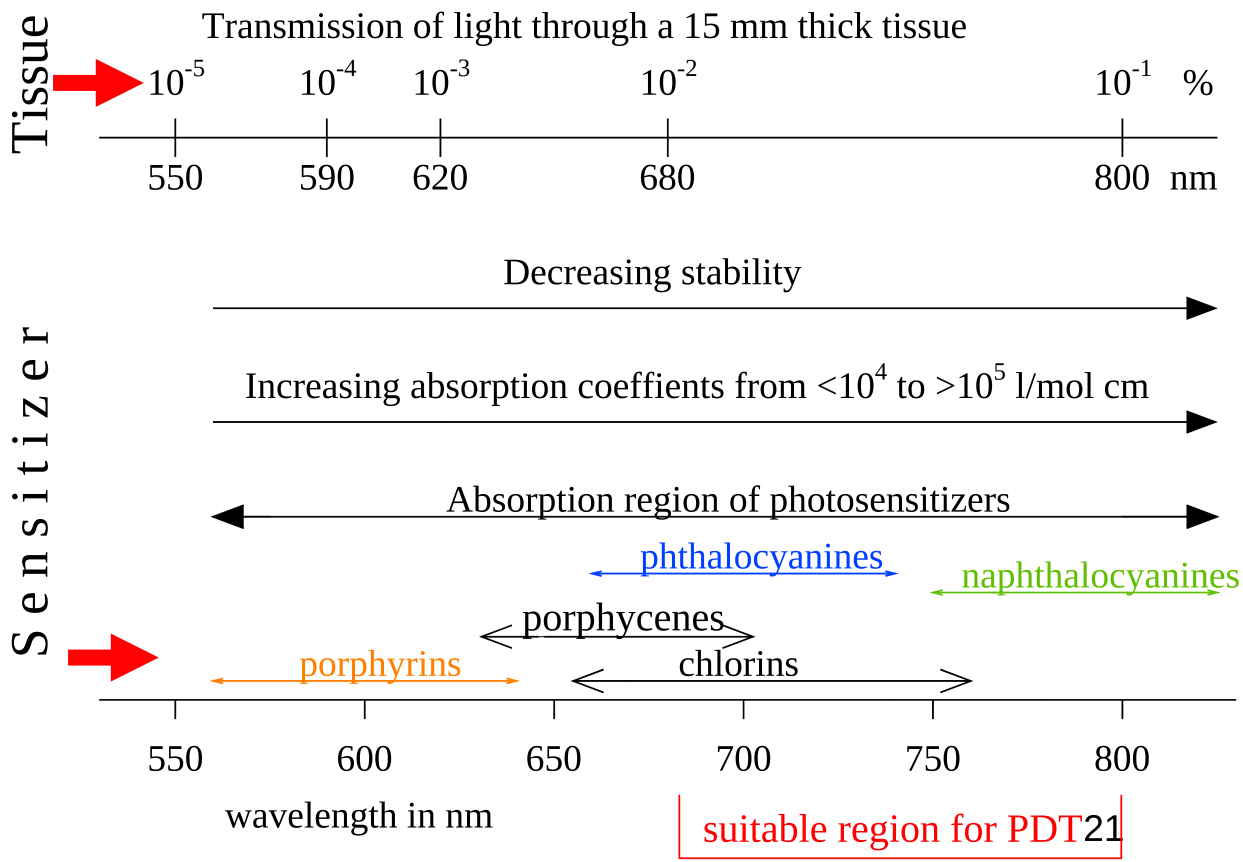


naphthalocyanine

λ 750 -815 nm

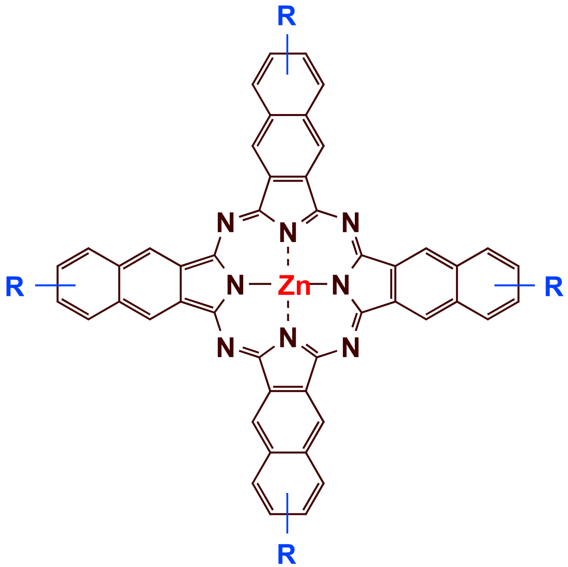
ϕ $^1O_2$ 0.4 - 0.5





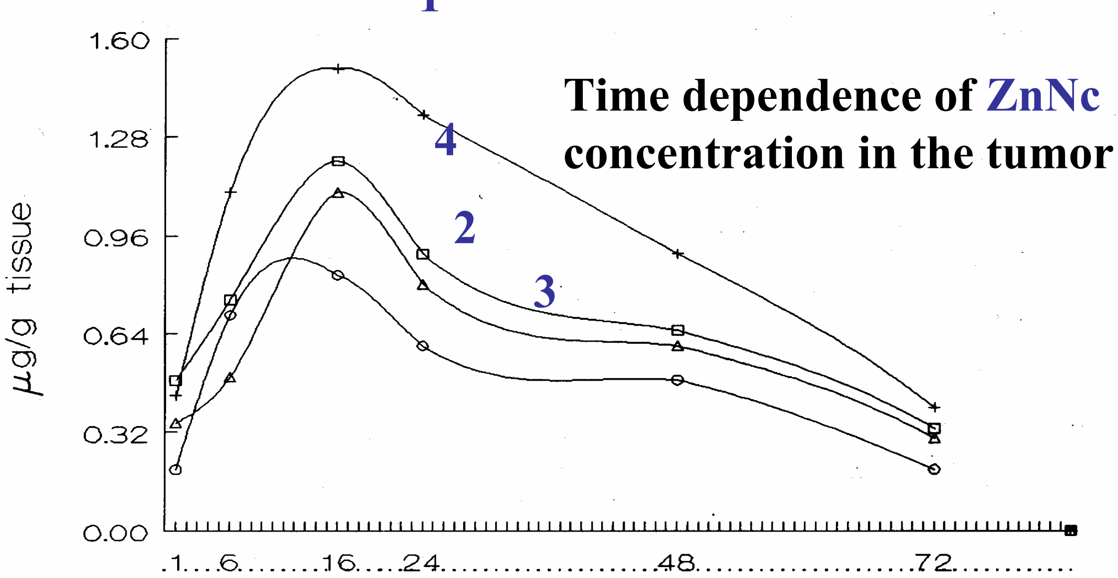
Naphthalocyanines for photodynamic cancer therapy

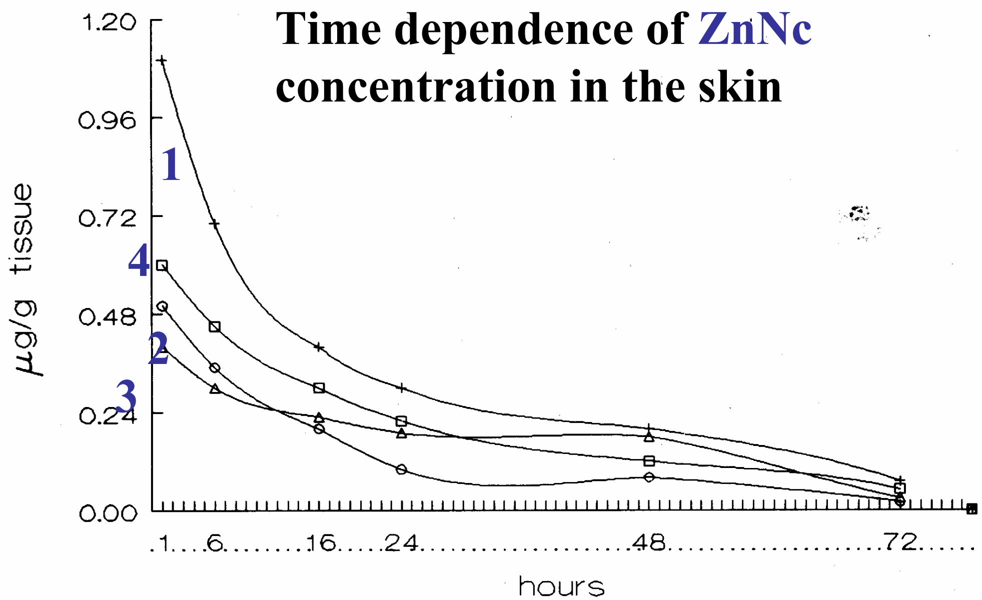
Zn naphthalocyanines
for Lewis lung carcinoma
of C57/Black mice.
Injected 0.25 mg per kg b.w.



	R
ZnNc 1	-H
ZnNc 2	-NH-Co-CH_3
ZnNc 3	-NH_2
ZnNc 4	-OCH_3

Distribution of Zn naphthalocyanines



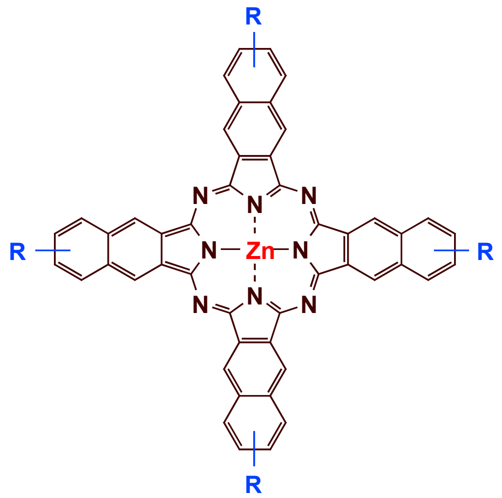


Porphyrins and porphyrazines for photodynamic cancer therapy

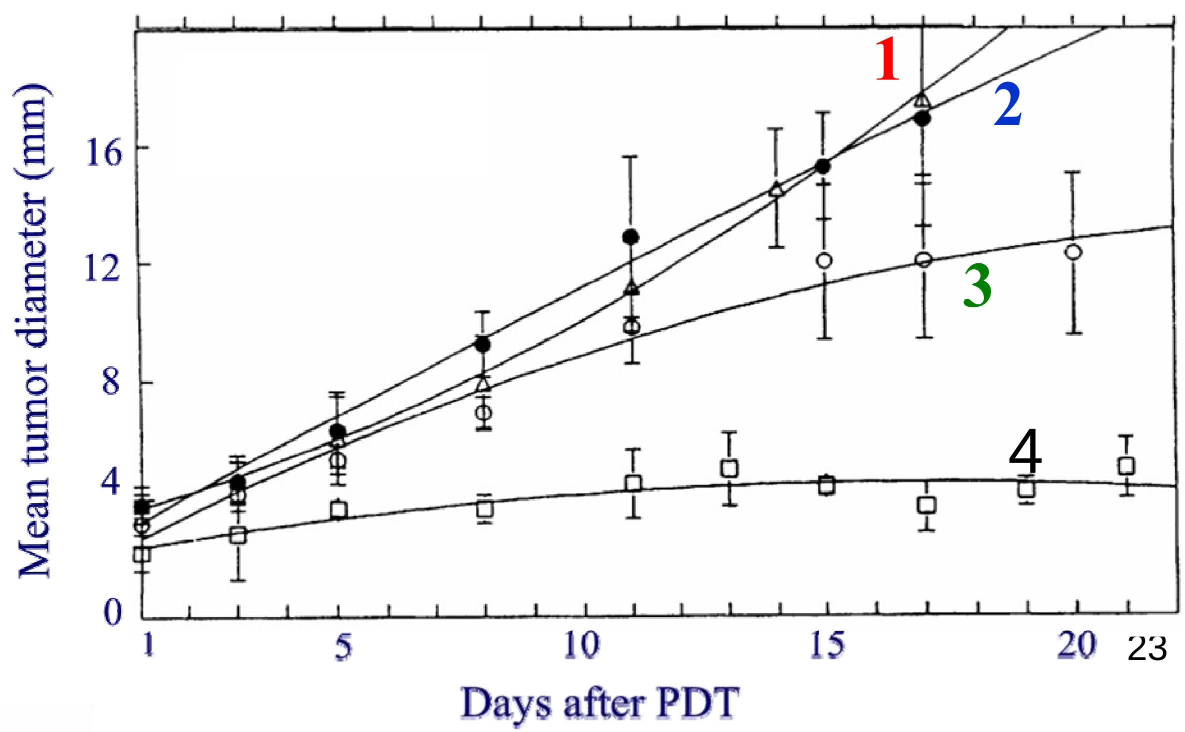
Comparison of pigmented melanoma growth rate in mice

- **Application of 3 mg HpD and only 0.3 mg other photosensitizers per kg body weight**
- **Irradiation in the absorption of the PS with 370 mW cm^{-2} (360 J cm^{-2})**

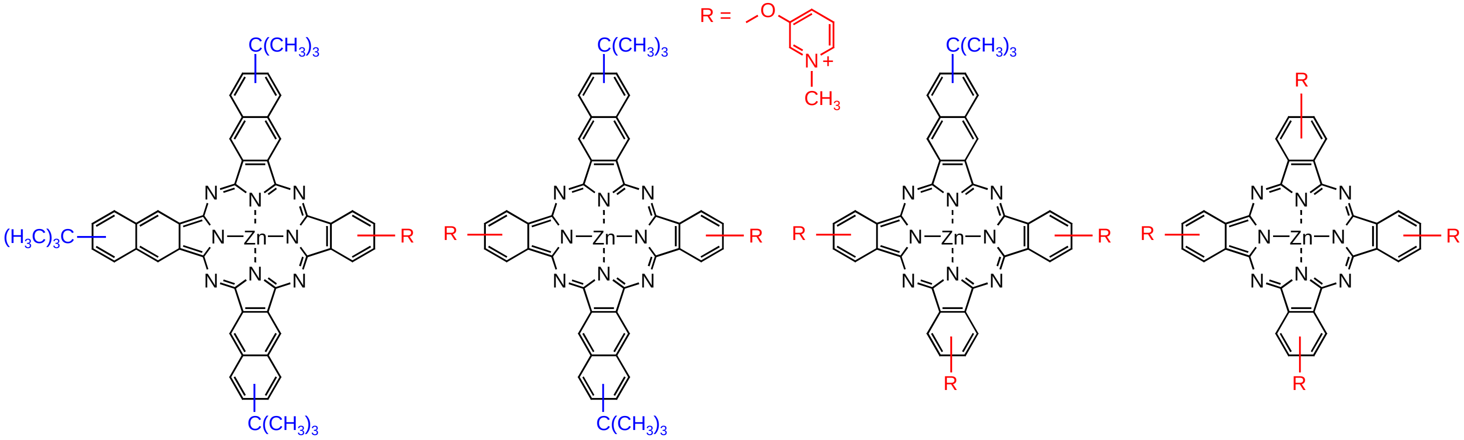
Δ : Control 1
● : Hematoporphyrin derivative (HpD) 2
○ : Zinc(II) phthalocyanine 3
□ : Tetra(acetamido)-substituted zin(II) naphthalocyanine 4



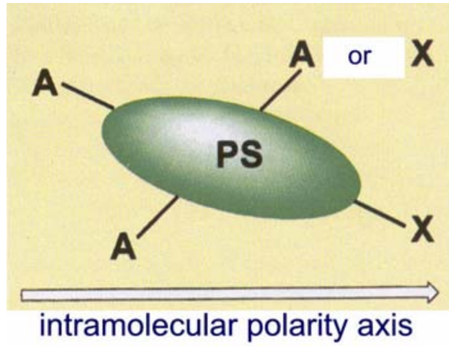
	R
ZnNc 1	-H
ZnNc 2	-NH-Co-CH_3
ZnNc 3	-NH_2
ZnNc 4	-OCH_3



In vivo activities of benzonaphthaoporphyrazines

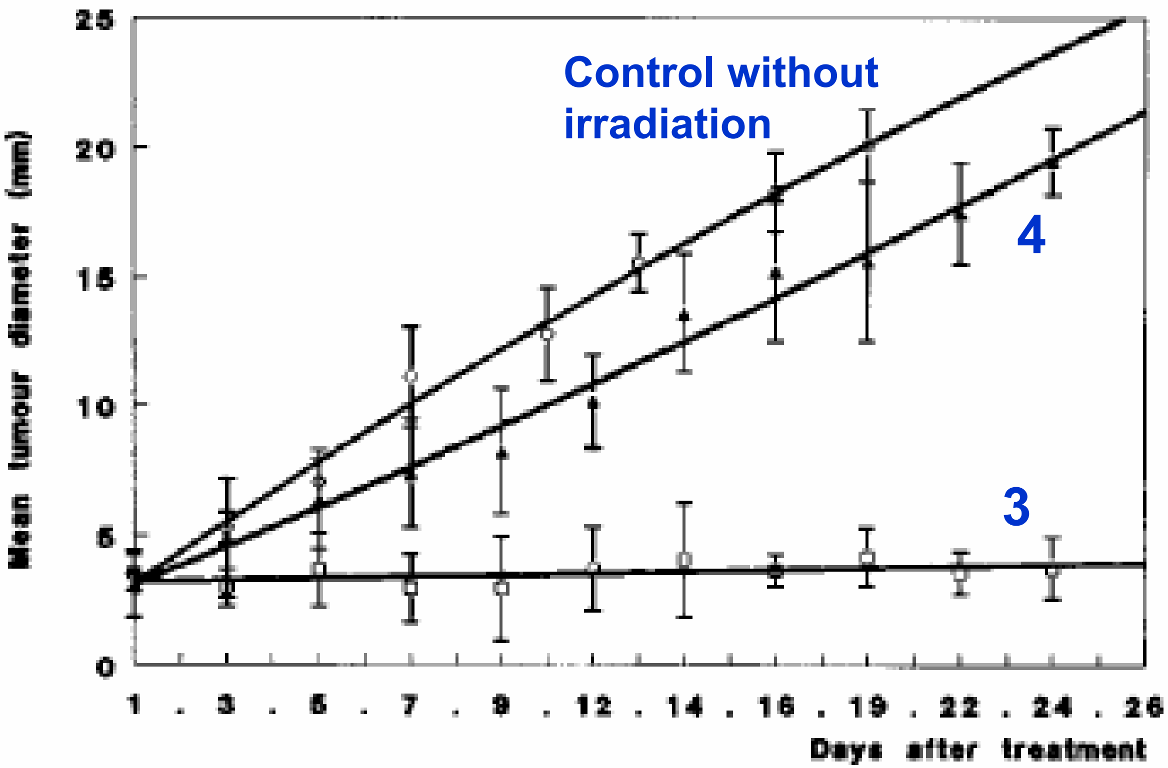


1 2 3 4



Photosensitizers (0.5 mg/kg) in an emulsion of cremophor. I.p.in mice bearing Lewis lung carcinoma. After 24 irradiation: fluence rate 380 mW/cm^2, Total fluence 360 J/cm^2.

Mean tumour diameter versus time after PDT.



5b. Photoinactivation of microorganisms (PDI) by phthalocyanine zinc complexes

V. Mantareva, et al; 2006 up to now

Bacterial suspension with cell densities of 10^6 till 10^9 cells/mL

↓

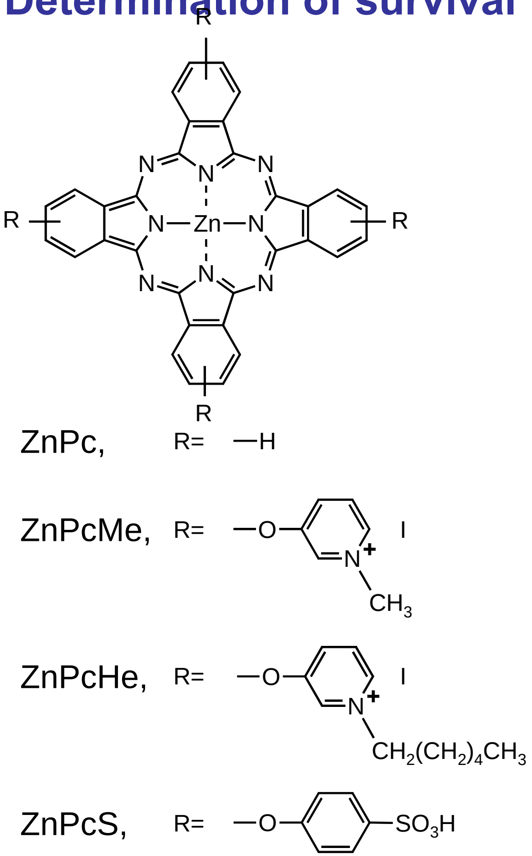
Incubation with 10^{-6} mol phthalocyanines for 10 min

↓

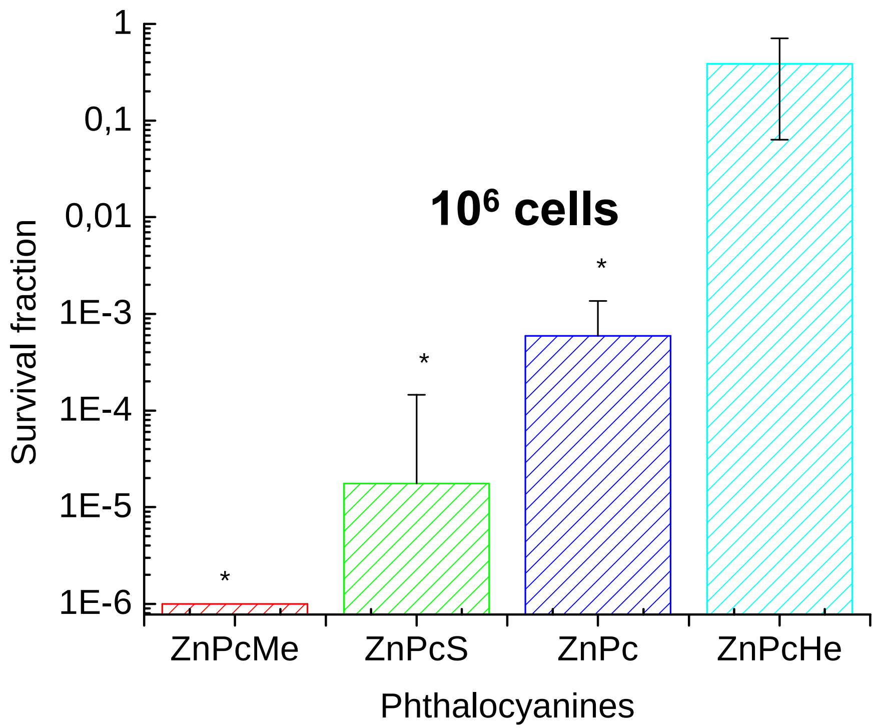
Irradiation for 2 till 10 min with light 675 nm

↓

Determination of survival fractions on agar plates



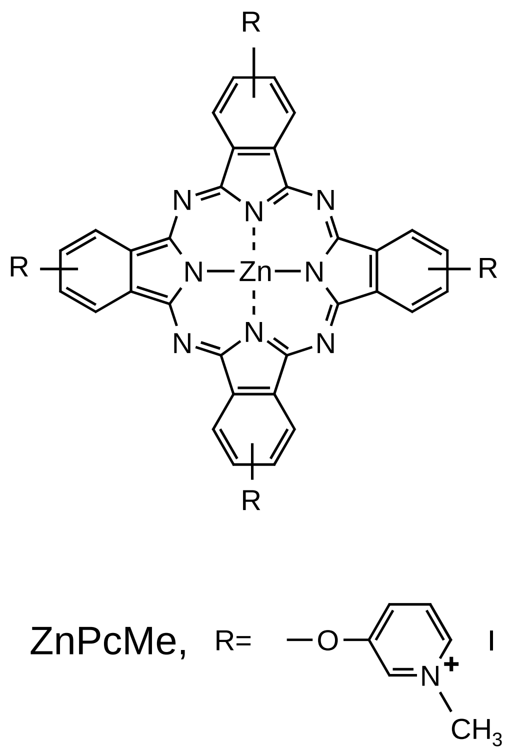
Photoinactivation of bacteria *Staphylococcus aureus*, after irradiation with 100 mW/cm² and 60 J/cm²

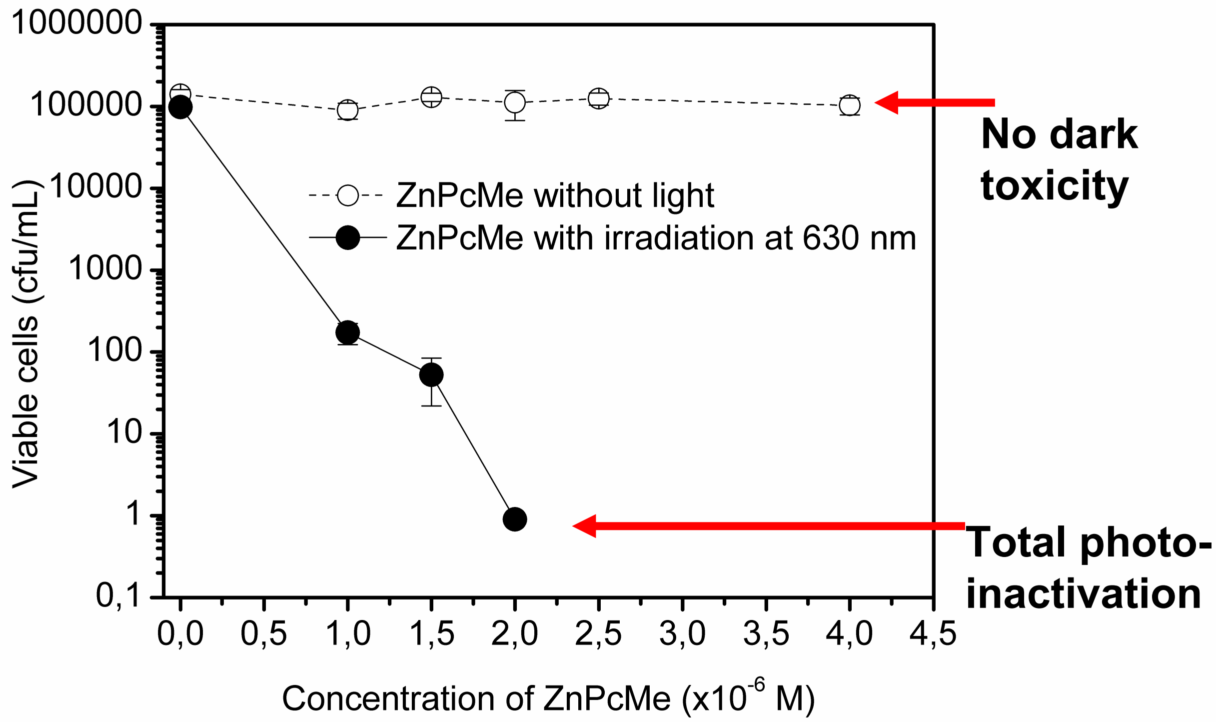


Photoinactivation (PDI) of microorganisms by phthalocyanine zinc complexes

Photoinactivation of Aeromonas hydrophila

Bacterial suspension with cell densities of 10^6 cells/mL
↓
Incubation with ~10^{-6} mol phthalocyanines for 10 min
↓
Irradiation for 2 till 10 min with light 635 nm (100 mW/cm^2, 30 J/cm^2
↓
Determination of survival fractions on agar plates





5c. Phthalocyanines as Photocatalysts

G. Schulz-Ekloff, R. Gerdes, G. Schneider, W. Spiller
Partly in collaboration with prosys company in Bremen

Investigated reaction:

- **Photooxidations of toxic pollutants for waste water cleaning**
- **Photooxidations for synthesis of fine chemicals (rose oxide)**

Our interests in this topic

- **Use of visible light or solar radiation: 1**
- **Reactions often in water: 1**
- **Use of oxygen (from air) for photooxidations: 1**

--

Number of so-called unlimited natural resources: 3

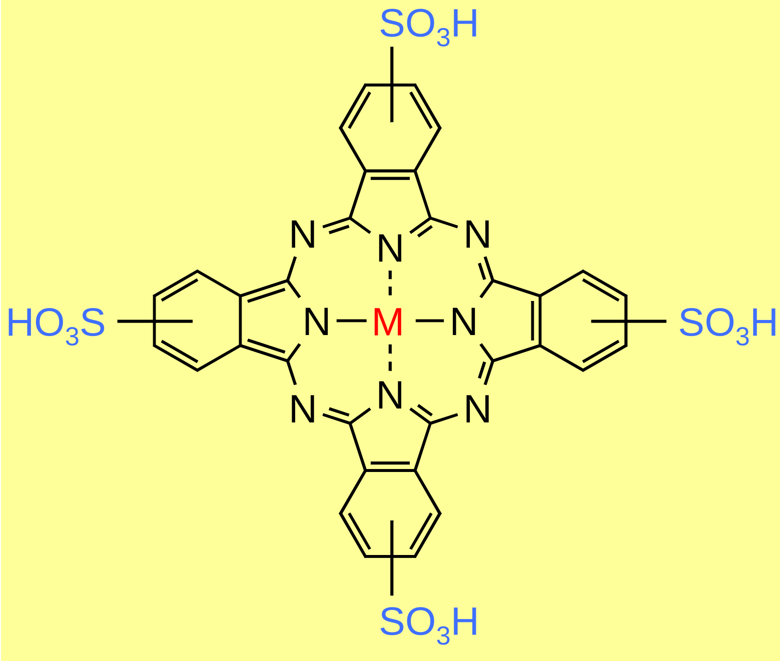
Example of a water soluble phthalocyanine

Catalysts

Open shell electron configuration

M = Co(II), Fe(II), V(IV)(O)

Interaction of the metal ion with substrate molecules



Photocatalysts

Closed shell electron configuration

M = Zn(II), Al(III)OH Si(IV)$(OH)_2$

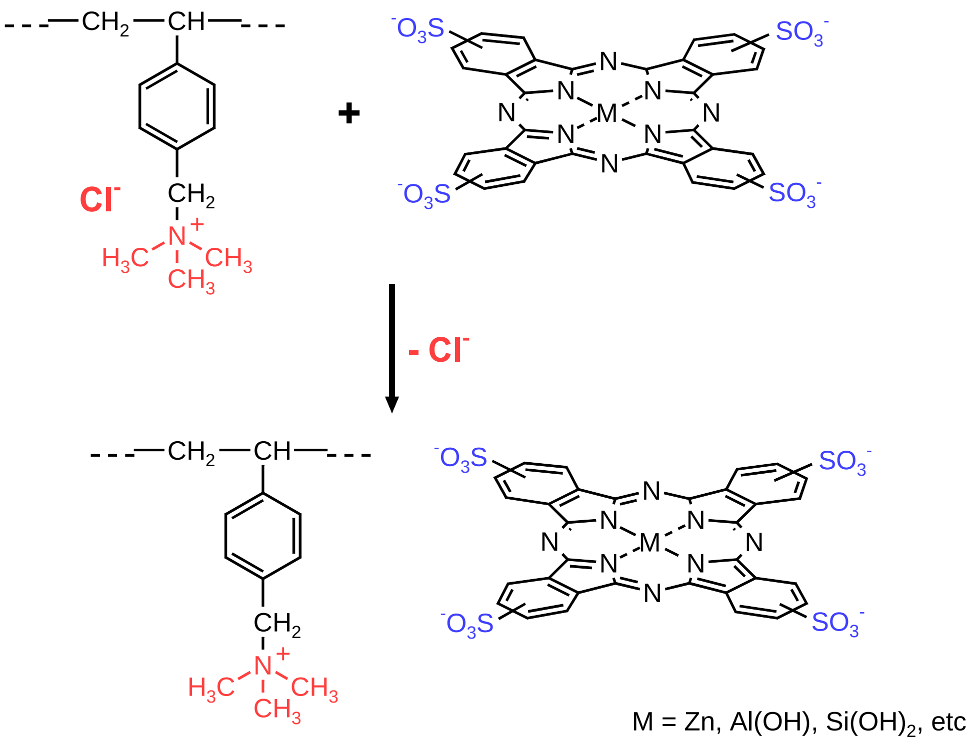
Under irradiation excited state of phthalocyanines and interaction with oxygen

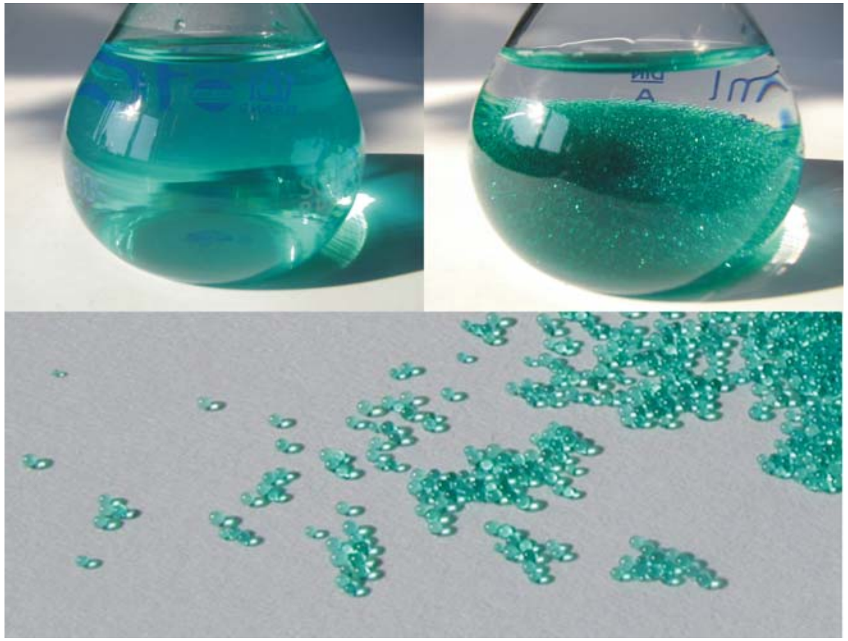
For detoxification of waste water from:
- sulfide
- organic sulfur compounds like thiols
- phenols, chlorinated phenols
- PAKs
photocatalytic oxidation are more effective than catalytic oxidations

Phthalocyanines at macromolecules: Heterogeneous photocatalyst

Advantages:
- **Easy separation from reaction products**
- **Easy reuse**

Polymer immobilized porphyrin derivatives by ion exchange at ion exchangers.
One example given:





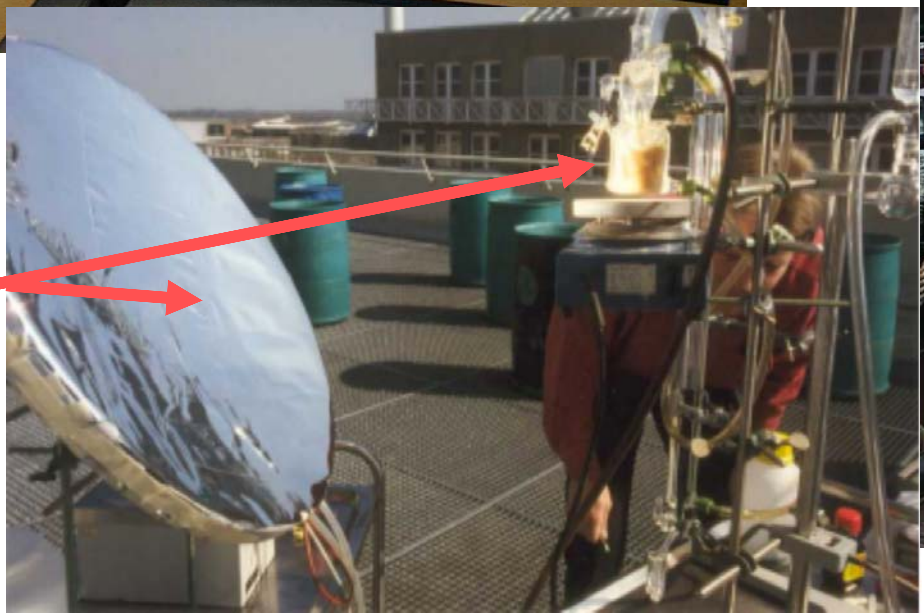
Loading: 4 – 10 µmol g^{-1}

Equipments

Laboratory equipment

Loop reactor for application

Solar reactor

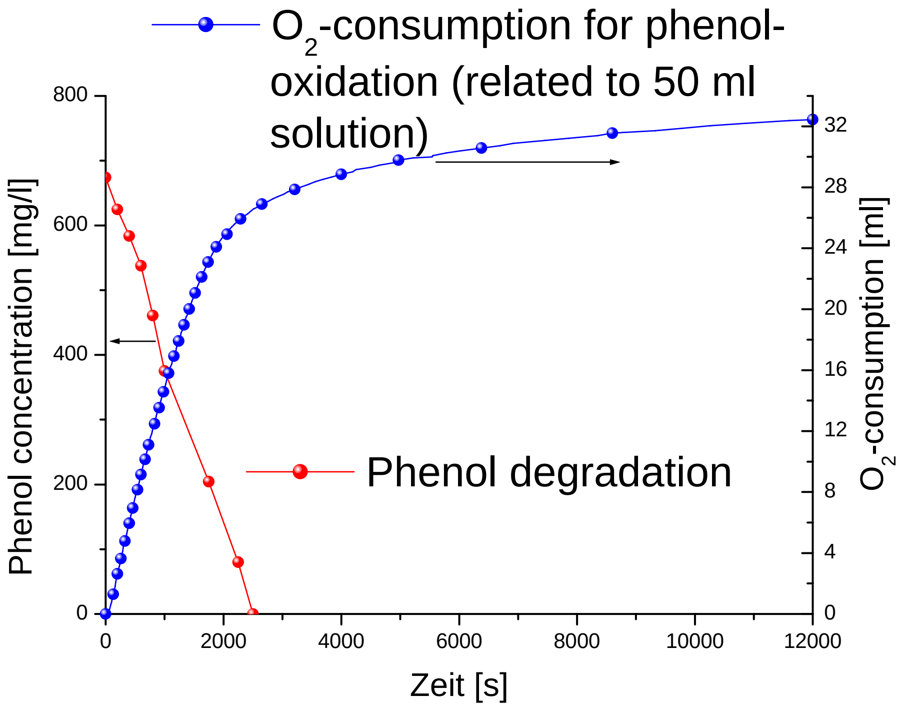


Photooxidation of Phenols with Phthalocyaninetetrasulfonic Acids in Solution

$$C_6H_5O^- + 3.5O_2 + 4HO^- \rightarrow CO_3^{2-} + H_2O + HCOO^- + {}^-OOC\text{-}C{=}C\text{-}COO^-$$

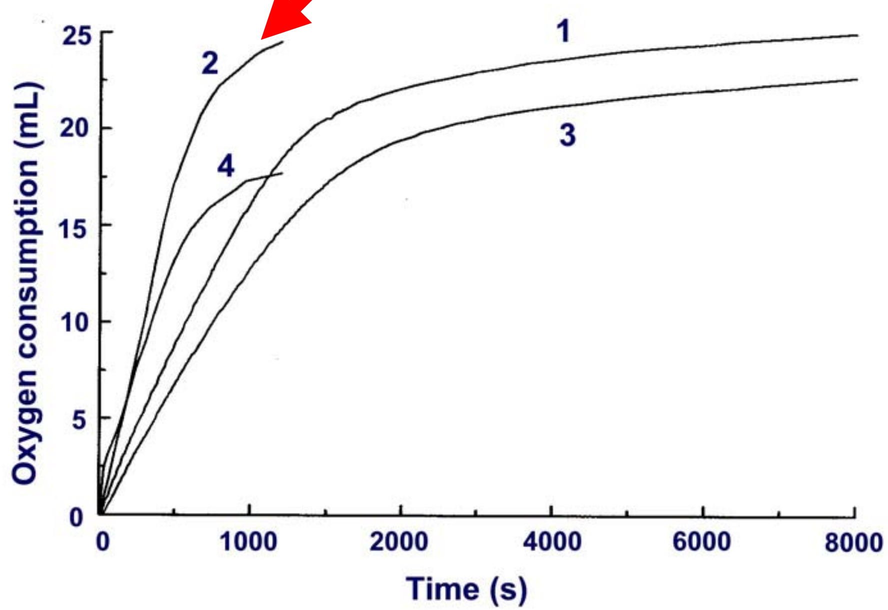
In aqueous alkaline solution; 0.36 mmol phenol, 0.25 µmol MPc molar ratio sulfide: MPc = 1400;

Photooxidation of phenol
pH 10



Photooxidation of 2-chlorophenol
pH 10

- **Irradiation with halogen lamp 180 mW cm^{-2}, 1 AlPc, 3 ZnPc**
- **Irradiation solar light 1000 mW cm^{-2} 2 AlPc, 4 ZnPc**



D. Wöhrle

prosys°
Gesellschaft für produktionsintegrierte Umweltsystemtechnologien und -management mbH

Degradation of industrial waste water with polymer bound $Si(X)_2$ phthalocyanine

Phenol containing waste water of the pharmaceutical industry

	Before:	After:	Degradation:
Phenol index:	2863 mg/l	43 mg/l	98,5 %
COD value:	136.752 mg/l	53.900 mg/l	60,6 %
pH value:	13,13	11,54	
Salt content:		40.000 mg/l	

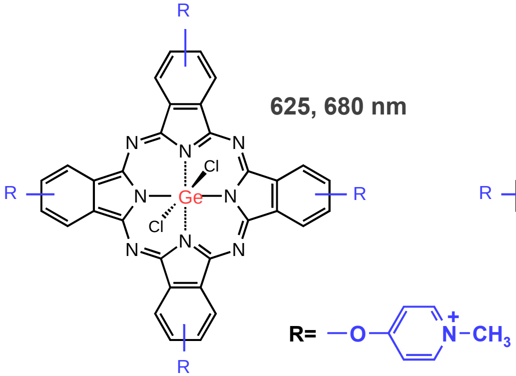
Polycyclic aromatic hydrocarbons (PAK) containing waste water

	Before	After	Degradation:
PAK amount:	640 µg/l	14 µg/l	97,8 %
COD value:	83 mg/l	< 15 mg/l	> 81,2 %
pH value	7,25	7,05	

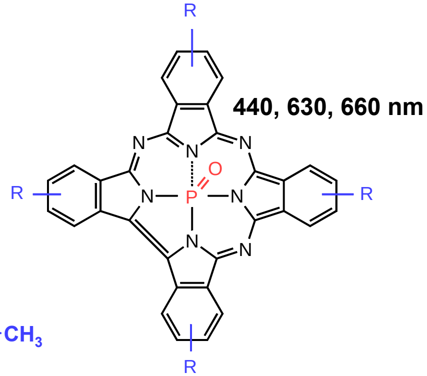
PAK: polycyclic aromatic compounds
CSB: sum of oxidizable compounds

Panchromatic light absorption and activity in photooxidations

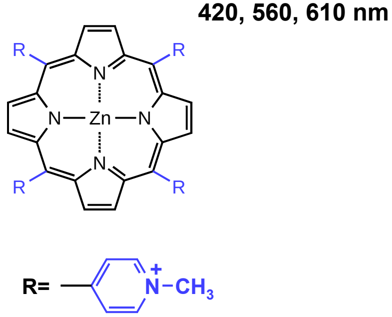
1 Phthalocyanines



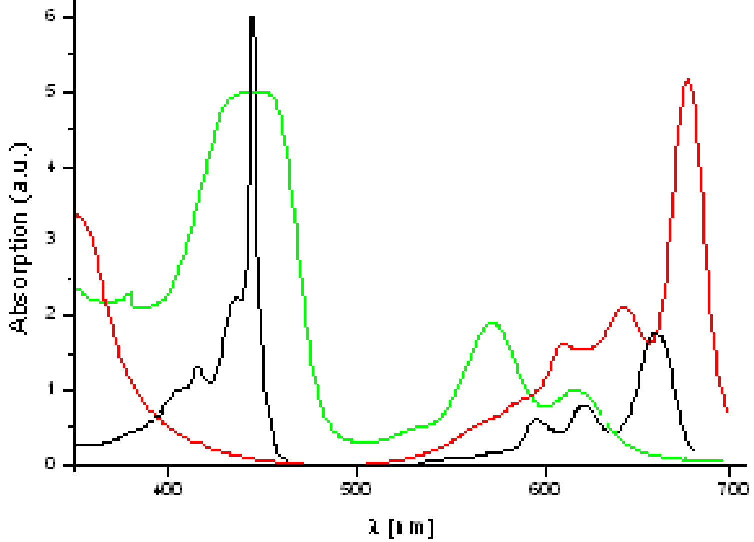
2 Corroles



3 Porphyrins

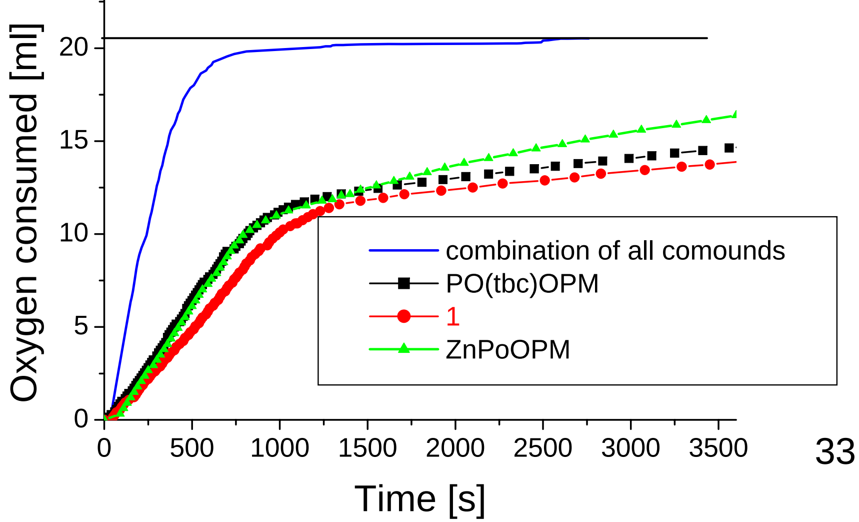


UV-Vis spectra (in water, SDS) of 1, 2, 3



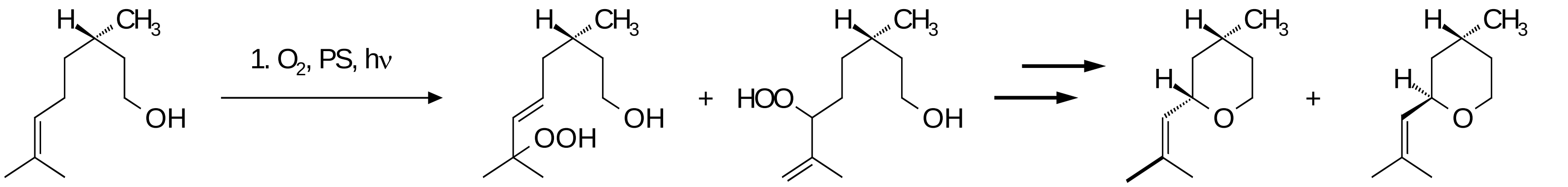
Photooxidation of 2-mercaptoethanol at pH 13 in water/SDS with 1, 2 ,3 and a combination of all three dyes

$$2\ R\text{-}S^- + 3\ O_2 \longrightarrow 2\ R\text{-}SO_3^- + H_2O$$



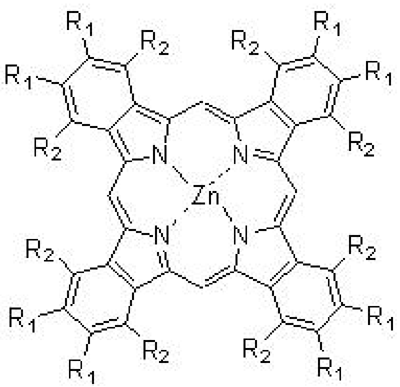
Photooxidation of citronellol for production of rose oxide

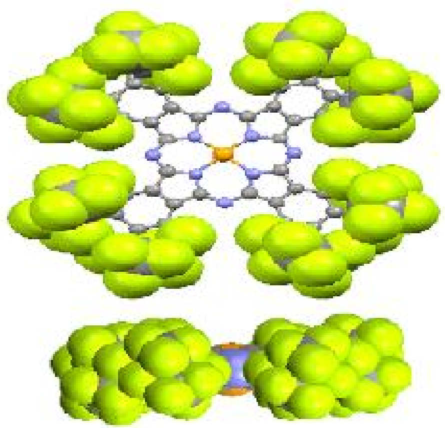
S. Gorun, Newark USA



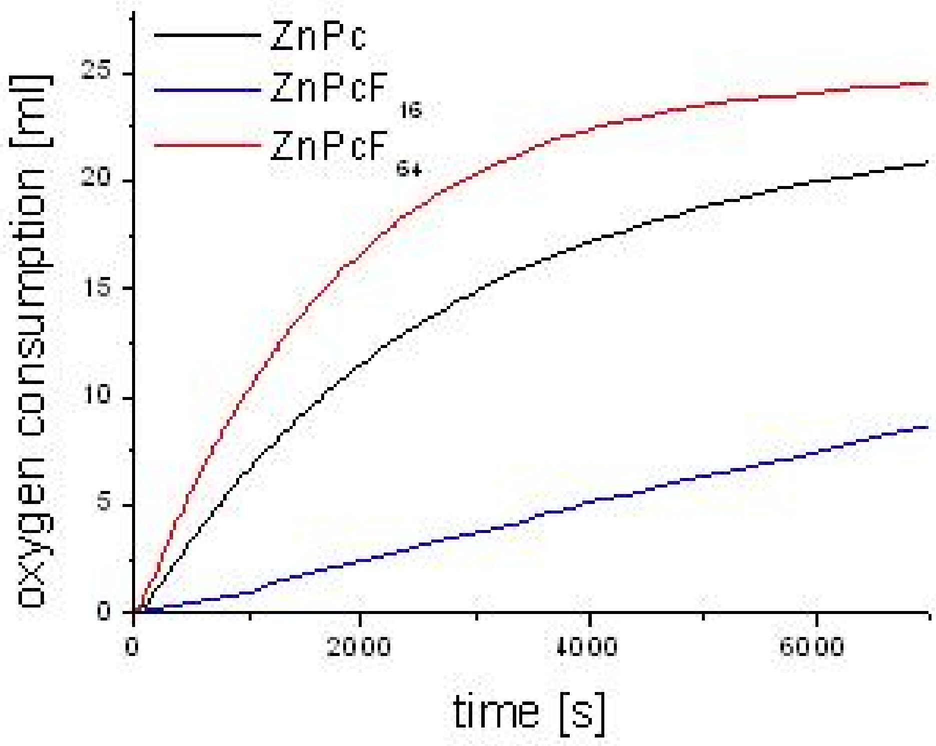
(S)-(-)-citronellol (2S,4R)-(-)- (2R,4R)-(-)

rose oxide





10^{-3} citronellol, 10^{-6} mol Pc

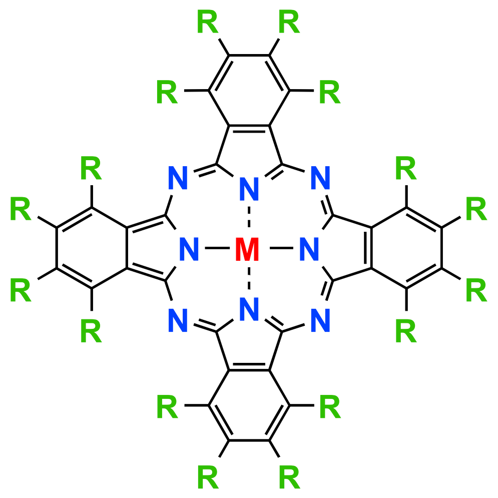


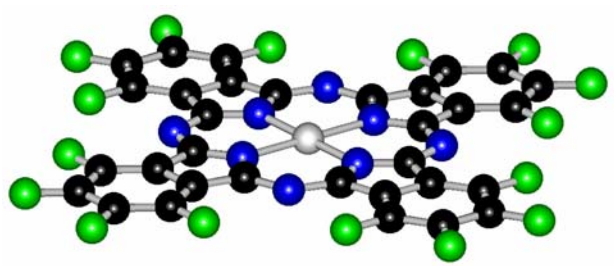
Compound	Φ $^1O_2$	Decom-position
ZnPc; R_1,R_2= -H	**0.42**	**13%**
$ZnPcF_{16}$: R_1,R_2= -F	**0.10**	**10%**
$ZnPcF_{64}$: R_1= $-C_3F_7$,R_2= -F	**0.81**	**0%**

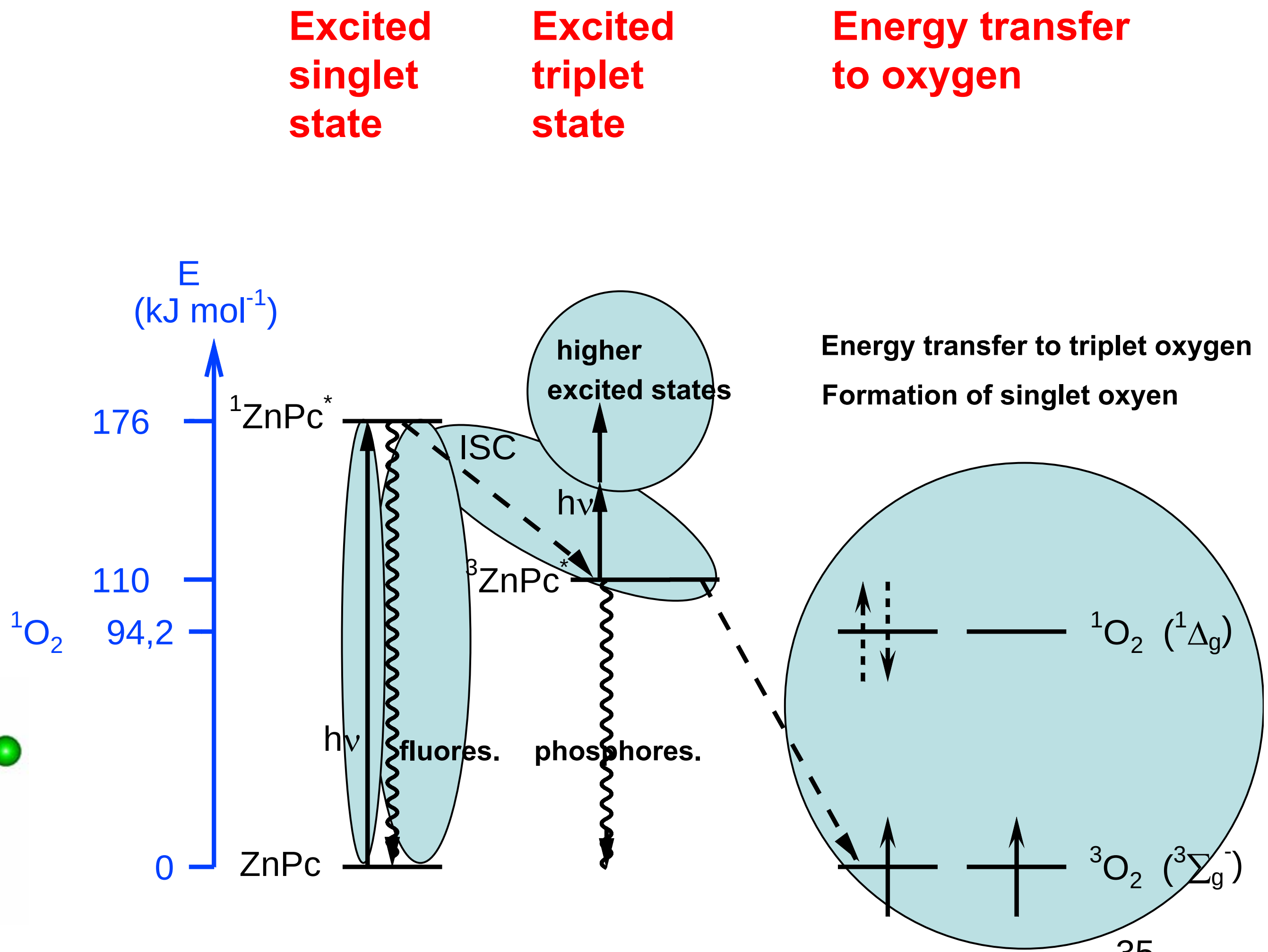
D. Wöhrle, Universität Bremen

The Excited State of Phthalocyanines - A Field of Many Applications

6. Summary

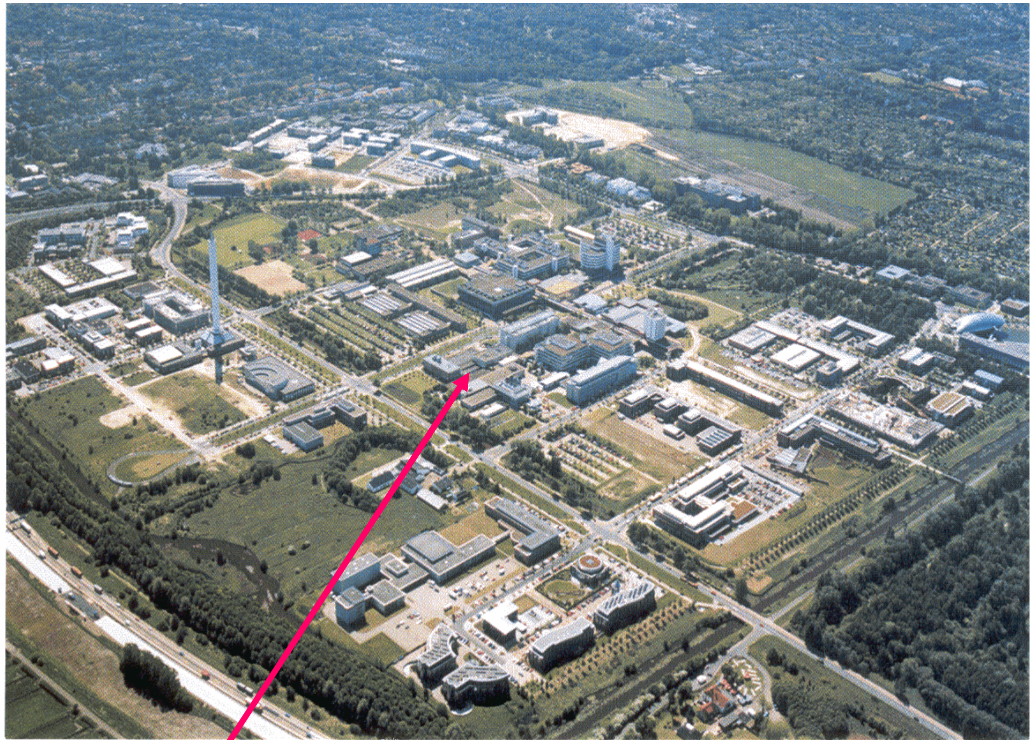






The Excited State of Phthalocyanines - A Field of a Many Applications

University

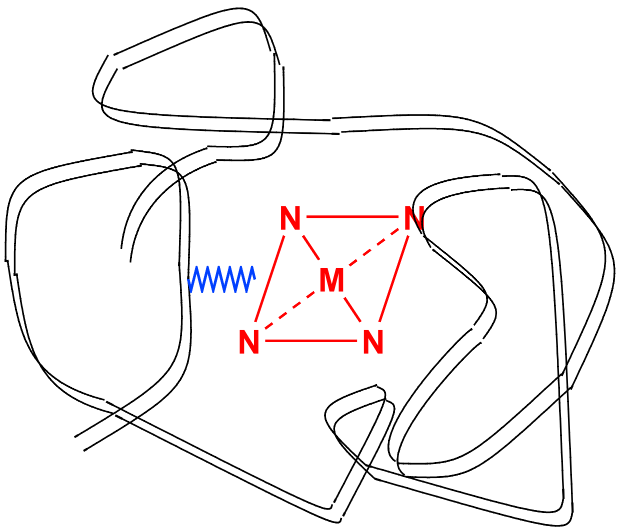


The Combination Phthalocyanines with Macromolecules

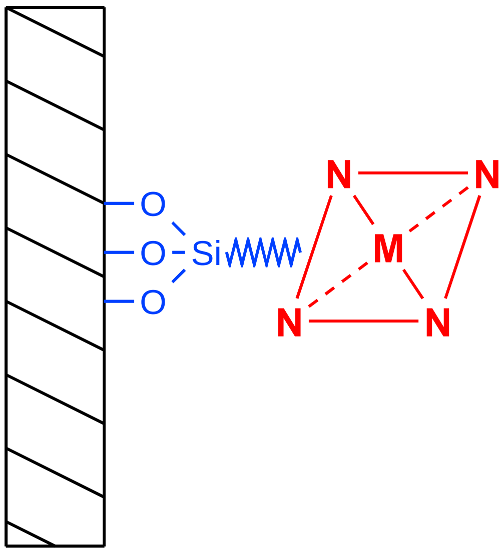
- The Way from Nature to New Synthetic Materials with Promising Properties

General Topic: MACROMOLECULAR METAL COMPLEXES

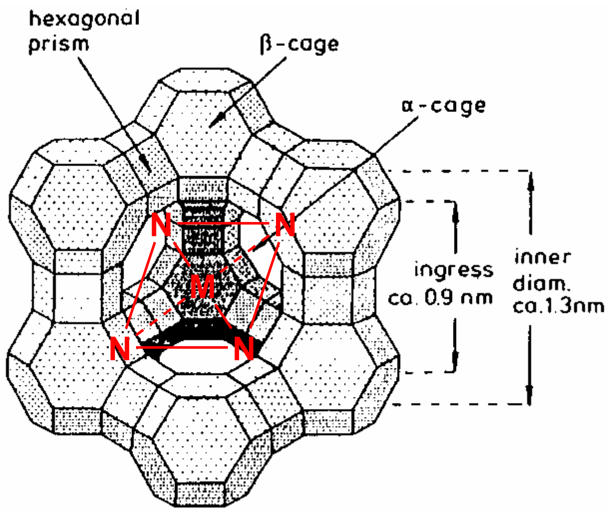
Combination with organic polymers



Combination with inorganic macromolecules, surfaces



Encapsulation in macromolecular molecular sieves



Photooxidation of toxic pollutants in waste water

Oxidation and Photooxidation of Sulfur Compounds and Phenols

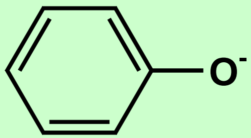
Catalytic oxidations

Mercaptan $2R\text{-}S^- + 0.5O_2 + H_2O \longrightarrow R\text{-}S\text{-}S\text{-}R + 2HO^-$

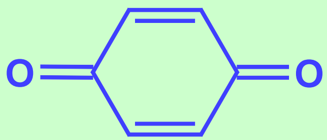
Sulfid: $2H\text{-}S^- + 2O_2 \longrightarrow S_2O_3^{2-} + H_2O$

$2H\text{-}S^- + O_2 \longrightarrow S_2 + 2HO^-$

Phenol:



$+ O_2 \longrightarrow$



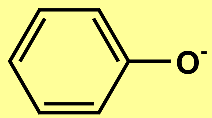
$+ HO^-$

Photocatalytic oxidations

Mercaptan $2R\text{-}S^- + 3O_2 \longrightarrow 2R\text{-}SO_3^- \ (SO_4^{2-})$

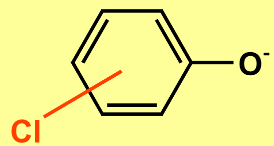
Sulfid: $H\text{-}S^- + 2O_2 + HO^- \longrightarrow SO_4^{2-} + H_2O$

Phenol:



$+ 3.5O_2 + 4\,HO^- \longrightarrow CO_3^{2-} + HCOO^- + 3H_2O$

Chlorophenols:



$\xrightarrow{O_2 + HO^-}$

$CO_3^{2-} + Cl^- + {}^-OOC\text{-}CH{=}CH\text{-}COO^- + ...$

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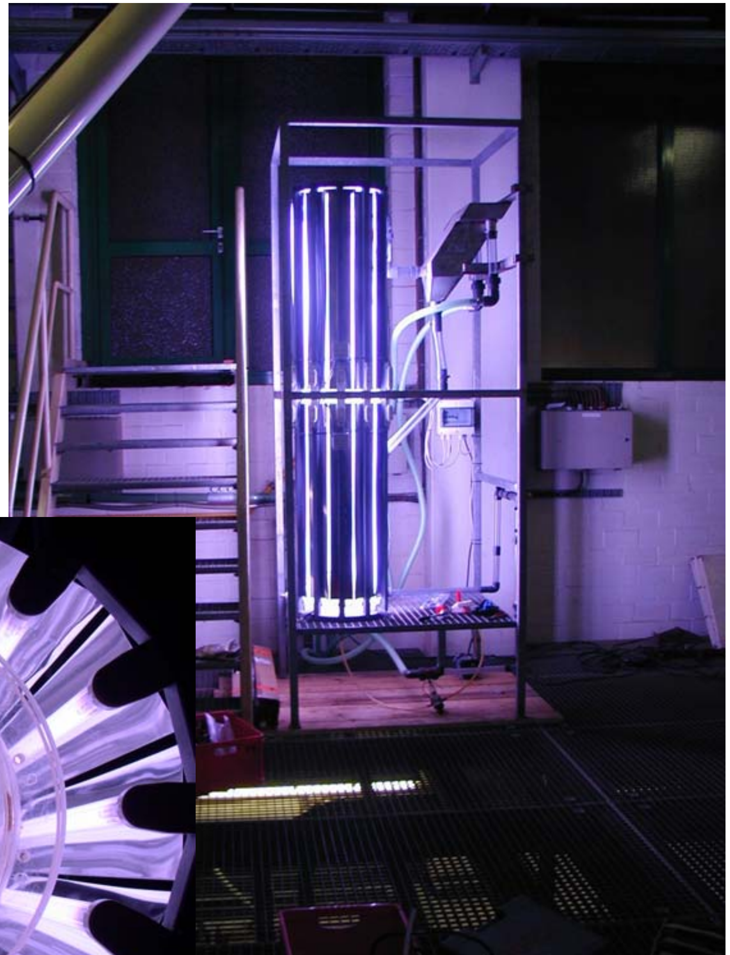
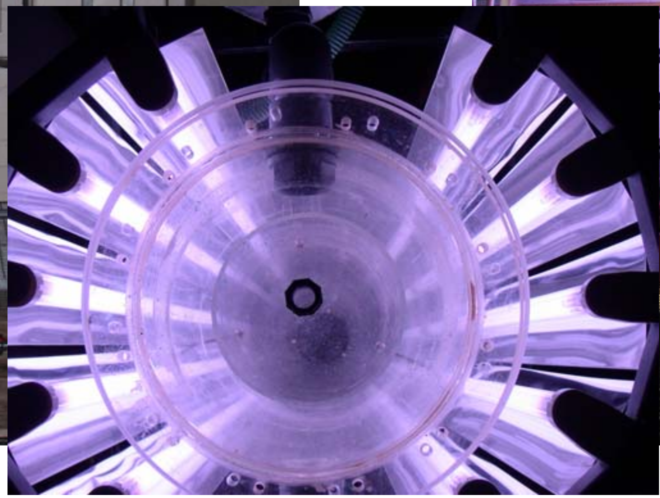
Commercial photoreactor with fluorescence lamps

Fluorescence lamps with a highest emission in the absorption region of the photocatalyst





Oxidations and Photooxidation of 2-Mercaptoethanol with Co and Zn Phthalocyaninetetrasulfonic Acid in Solution

G. Schneider

Catalysis: $2R\text{-}S^- + 0.5O_2 + H_2O \rightarrow R\text{-}S\text{-}S\text{-}R + 2HO^-$
Photocatalysis: $2R\text{-}S^- + 3O_2 \rightarrow 2R\text{-}SO_3^-$ (SO_4^{2-})

In aqueous alkaline solution(pH 13); molar ratio sulfide: ZnPc = 1400; illuminaton with 180 mW cm^{-2}

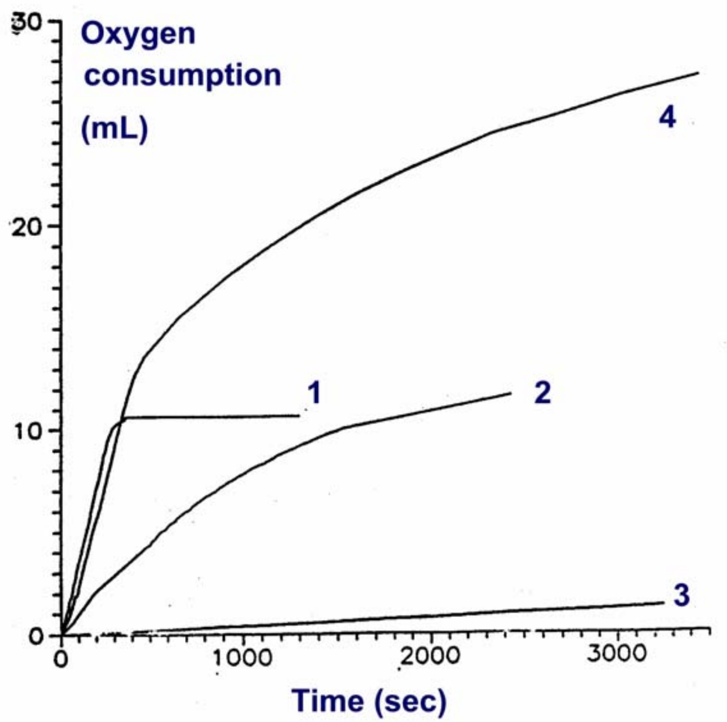
Oxidation and photooxidation with low molecular catalysts and photosensitizers

1 with $CoPc(SO_3^{-)})_4$ dark and under illumin.

2 with $CoPc(SO_3^-)_4$ dark and under illumin., presence of detergent CTAC

3 with $ZnPc(SO_3^-)_4$ dark, presence of CTAC

4 with $ZnPc(SO_3^-)_4$ illumin, presence of CTAC



Photooxidation of Phenol with Phthalocyaninetetrasulfonic Acids

R.Gerdes, O. Bartels

$$C_6H_5O^- + 3.5O_2 + 4HO^- \rightarrow CO_3^{2-} + H_2O + HCOO^- + {}^-OOC\text{-}C{=}C\text{-}COO^-$$

In aqueous alkaline solution; molar ratio sulfide: MPc = 1400 or 40 ;
Irradiation of a glass reactor with 180 mW cm^{-2} of a tungsten halogen lamp

Reuse of $SiPc(SO_3^-)_4$ on polymer