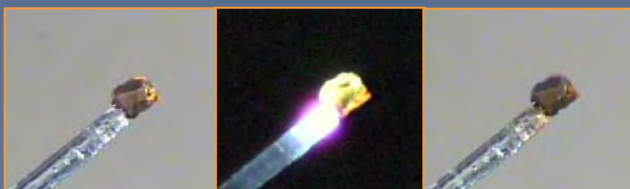




***Chemical reactions depend on the environment:
how do we study them on fs time-scales?***



International Workshop on Femtosecond X-ray experiments at
the European XFEL, Dec. 9-11, 2009

This Talk

- Chemical reactions
- Excited States
- Photochemical mechanisms
and environmental factors
- Measurements
- Final Remarks

**small molecule reactions as triggers
for biochemical reactions**

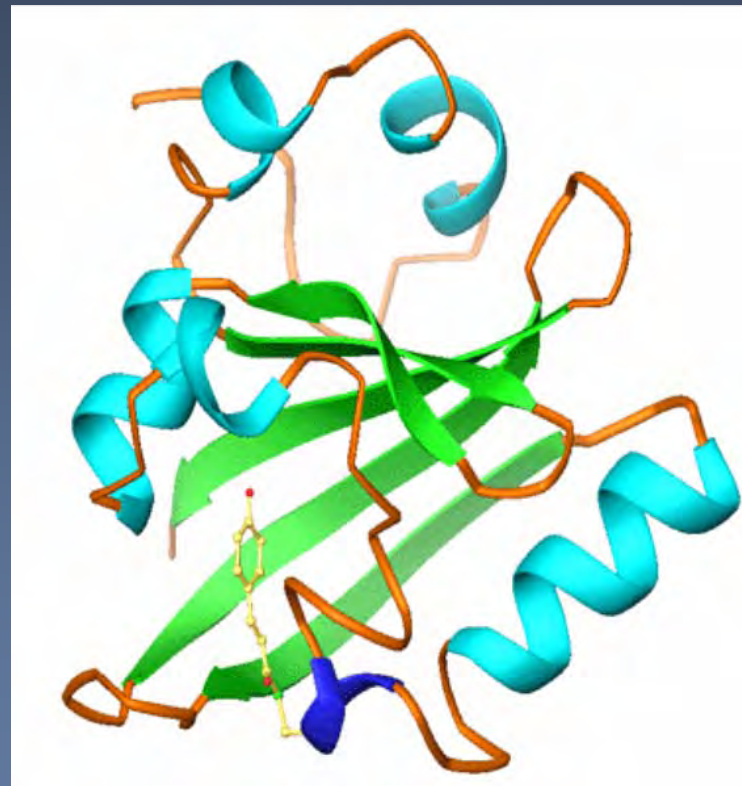
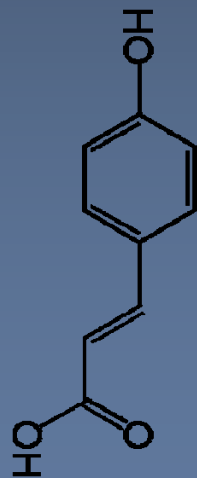
signal transduction in living systems

Isomerization reactions

Photoactive Yellow Protein: A reaction triggered by a trans-cis isomerization

fully reversible photocycle that lasts on the order of 1 s

**First step:
trans-to-cis isomerization
of coumaric acid**

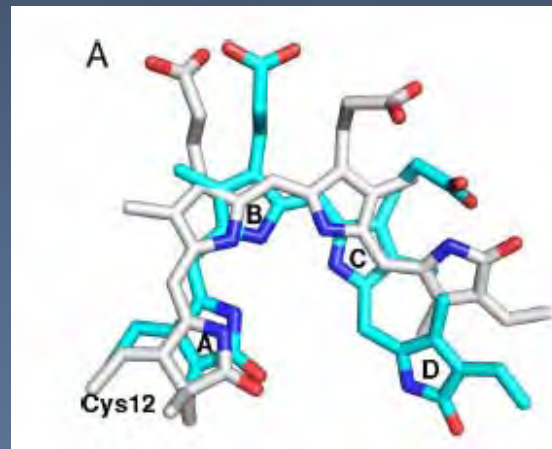
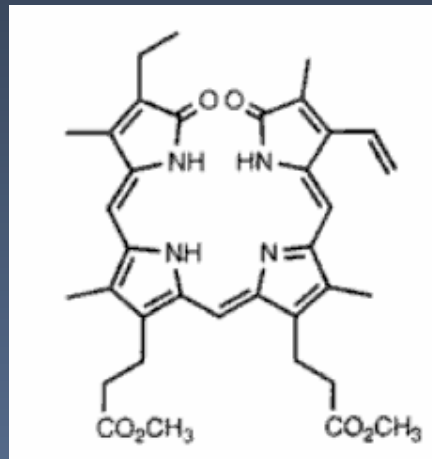


E. D. Getzoff, K. N. Gutwin, U. K. Genick, *Nature Structural Biology*, 10, 663-668, 2003
K. Moffat, S. Anderson, P. Anfinrud et al. *Structure*, 12, 1039-1045, 2004

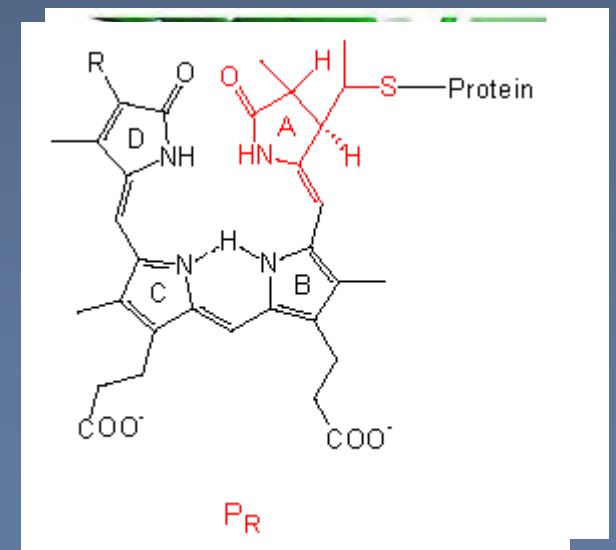
Crystal structure of *Pseudomonas aeruginosa* bacteriophytochrome: Photoconversion and signal transduction

X. Yang, J. Kuk, K. Moffat
PNAS, 105, 14715-14720, 2008

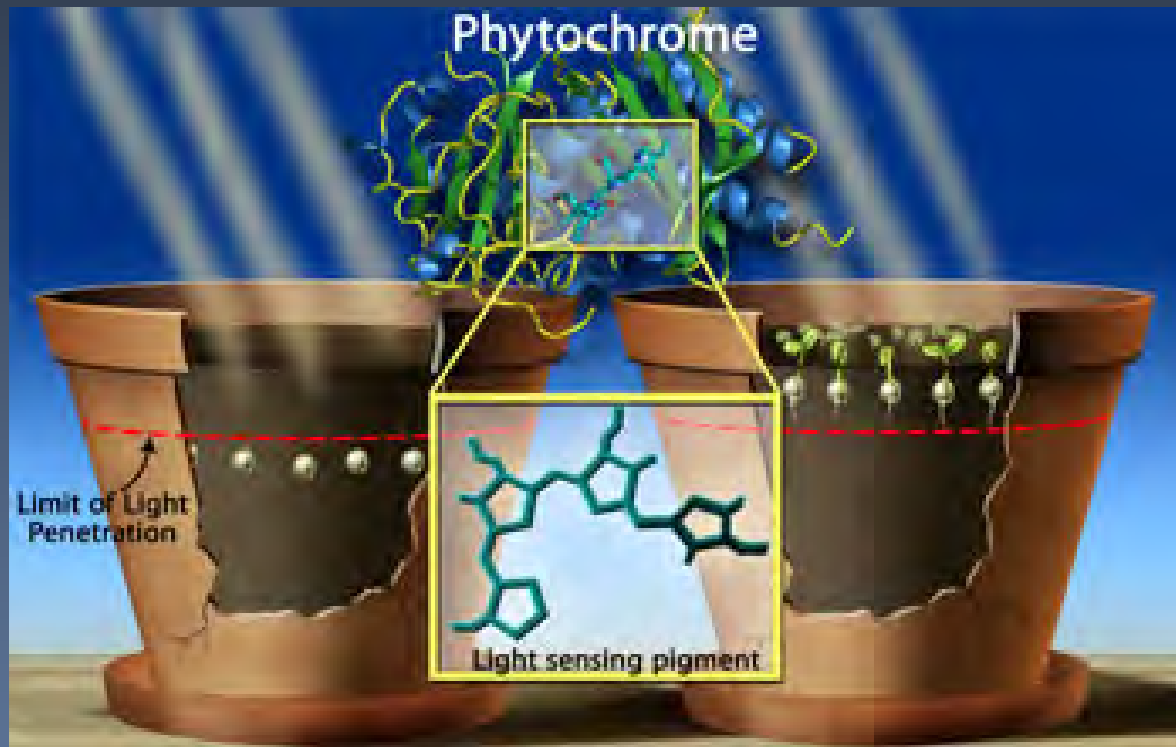
Phytochromes are red-light photoreceptors that regulate light responses in plants, fungi, and bacteria via reversible photoconversion between red (Pr) and far-red (Pfr) light-absorbing states.



cyan $\xrightarrow{h\nu}$ grey



seed germination



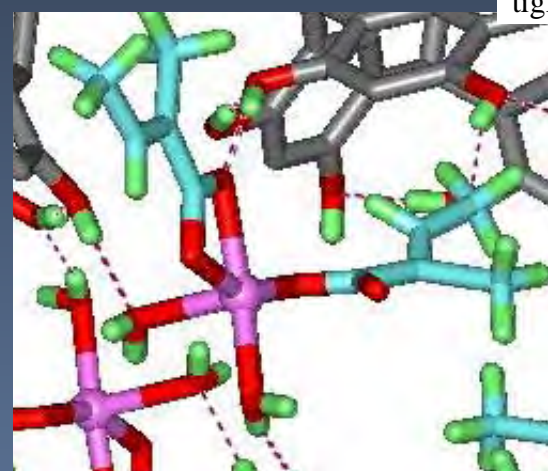
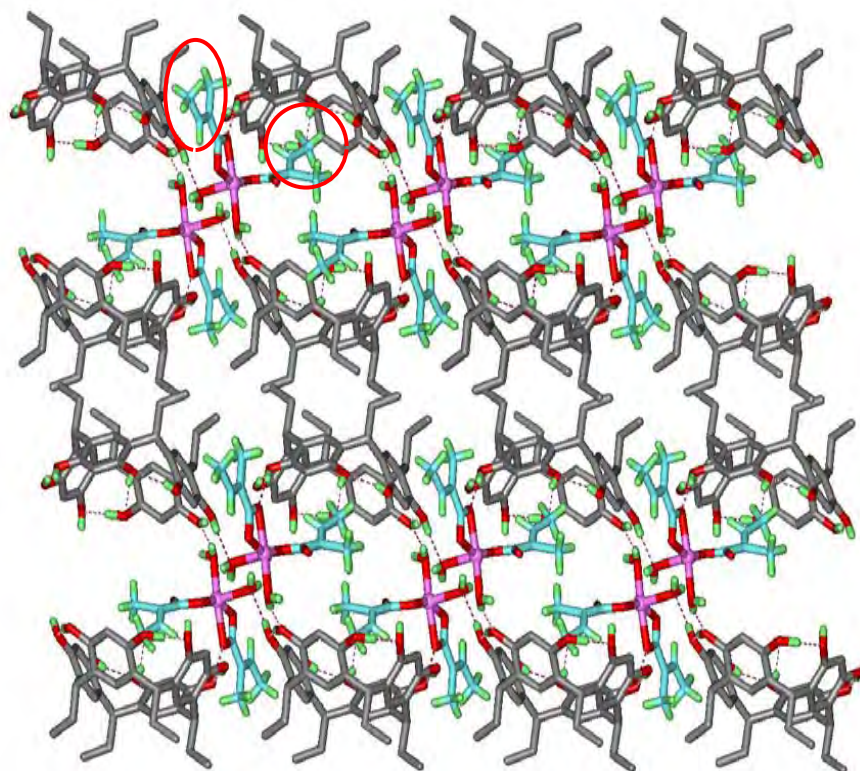
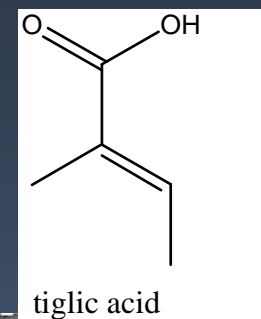
*N. Rager-Fuller, NSF; J.R. Wagner, Univ. of Wisconsin-Madison;
J.S. Brunzelle, Northwestern Univ.,
and K.T. Forest and R.D. Viestra, Univ. of Wisconsin-Madison.*

Small molecule prototype systems:
an example: study of kinetics of the
reaction in the solid state

S.- L. Zheng *et al.* Chem. Eur. J. 2008,14, 706-713

Zn(tiglic acid)₂ (H₂O)₂ inclusion compound

90 K, using focused He-Cd Laser , 325 nm



tiglic acid in 2 different cavities

Viewed along *a*-axis

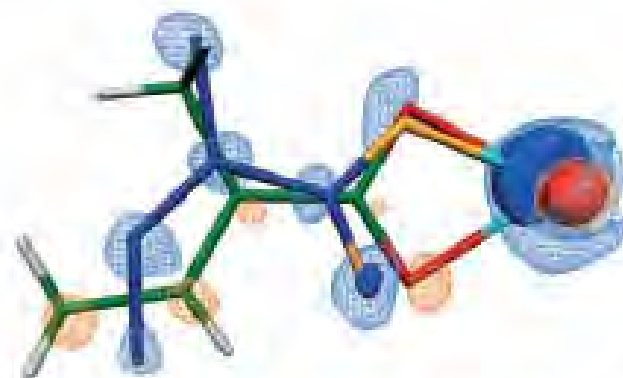
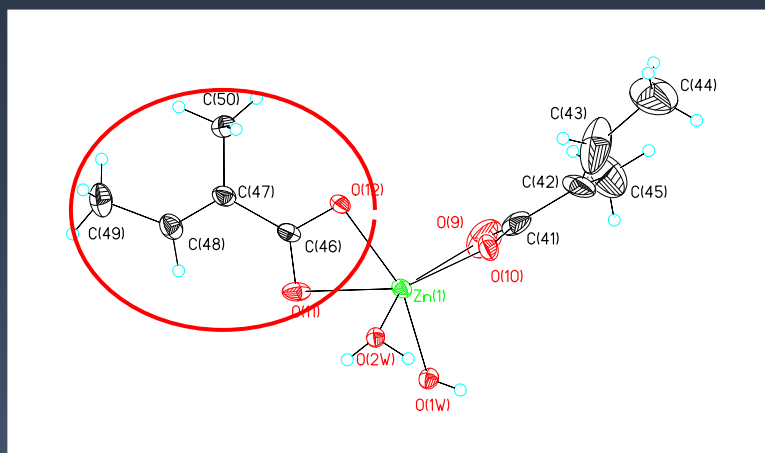
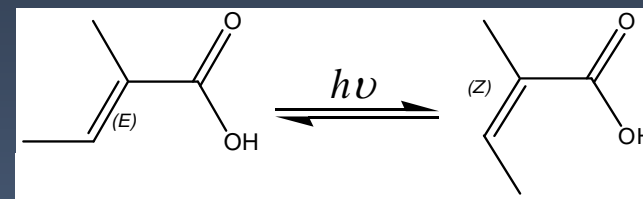
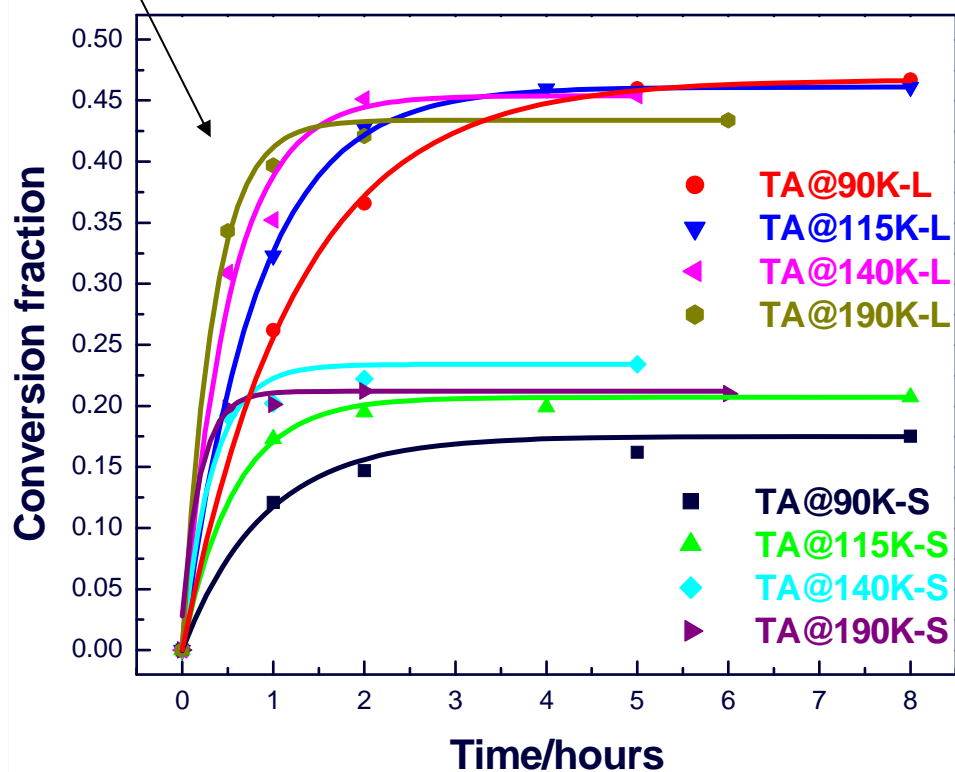


Figure 3. Difference map of the TA@S complexed to Zn^{II} after 2 h exposure (blue: 2.0, light blue: 1.0, orange: -1.0, red: -2.0 $e \text{ \AA}^{-3}$).

Kinetic analysis: temperature dependence effect of the cavity size

rate increases with T



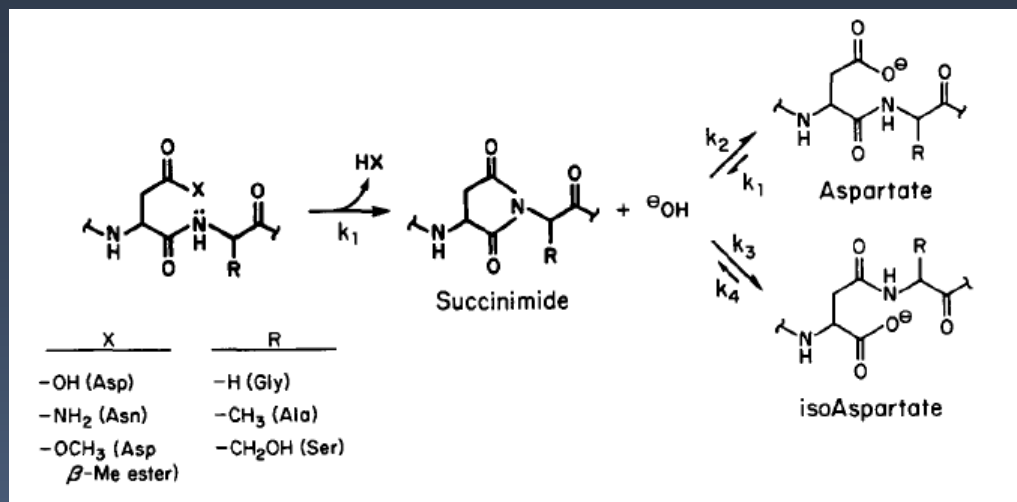
large cavity

small cavity

exposure, 325 nm 45mW He-Cd laser

Ring closure reactions

Spontaneous degradation of proteins: R.C. Stephenson and Clarke J. Biol. Chem. 264, 6164 (1989)



Homochirality and Life

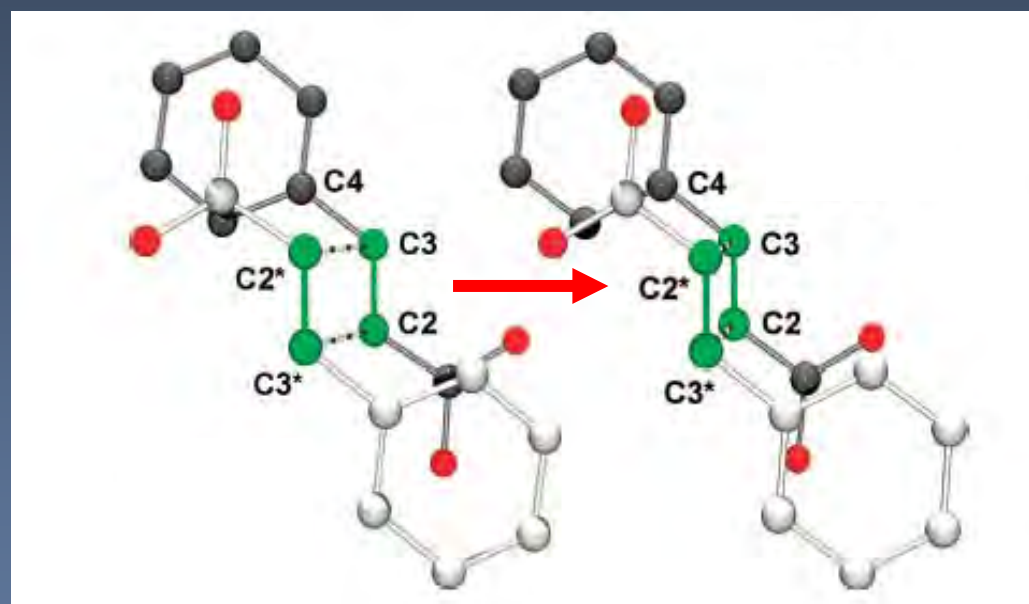
NORIKO FUJII, TAKESHI SAITO
Research Reactor Institute, Kyoto University Kumatori, Sennan, Osaka 590-0494, Japan

The Chemical Record, Vol. 4, 267-278 (2004)

In aged human alpha A-crystallin in eyes, two specific sites of Asp-58 and Asp-151 were found to be highly inverted to the L-enantiomer to D-enantiomers (D/L ratio: 3.1 for Asp-58, 5.7 for Asp-151).

A D/L ratio higher than 1.0 is remarkable since it is not defined as racemization, but as the inversion of the configuration of L-asp to D-Asp.

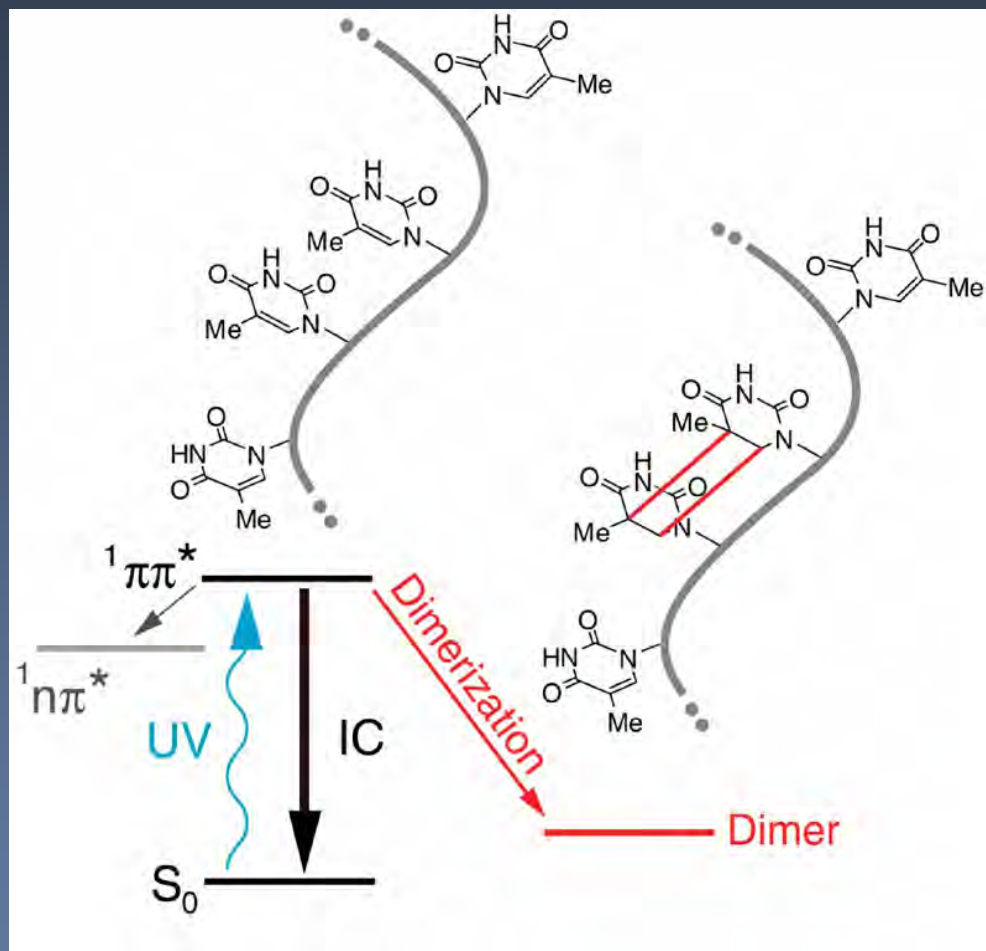
Dimerization reactions



Benedict and Coppens, JACS 2009

Thymine Dimerization in DNA Is an Ultrafast Photoreaction

W. J. Schreier, *et al*, *Science* 315, 625 - 629, 2007

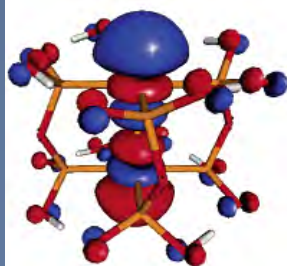
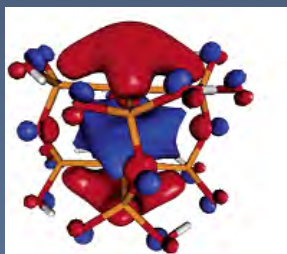
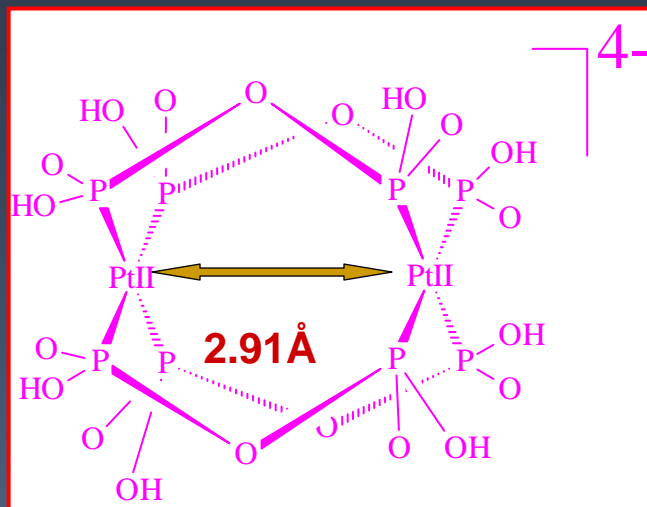


This Talk

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$[Pt_2 (P_2O_5H_2)_4]$ 'PtPop'

50 μ s lifetime at 17K



Contraction of Pt-Pt on excitation:

Diffraction

Solid State

Kim et al 2002, 17K: **0.29(8) Å**

Ozawa et al 2003 54K: **0.23(4) Å**

Solution (aqueous)

Christensen et al 2009 RT: **0.24(6) Å**

EXAFS

Solution (ethanol)

van der Veen et al 2009 RT: **0.31(5) Å**

Spectroscopy

Solid State

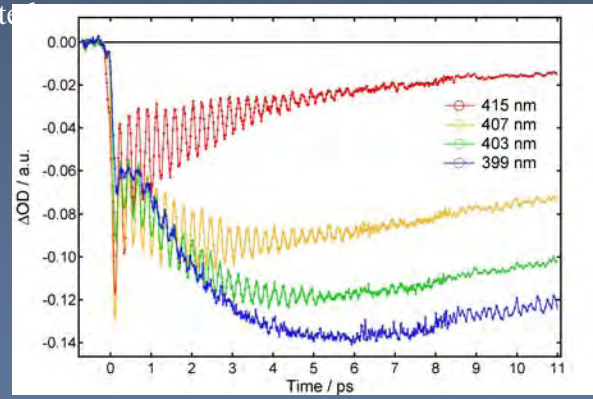
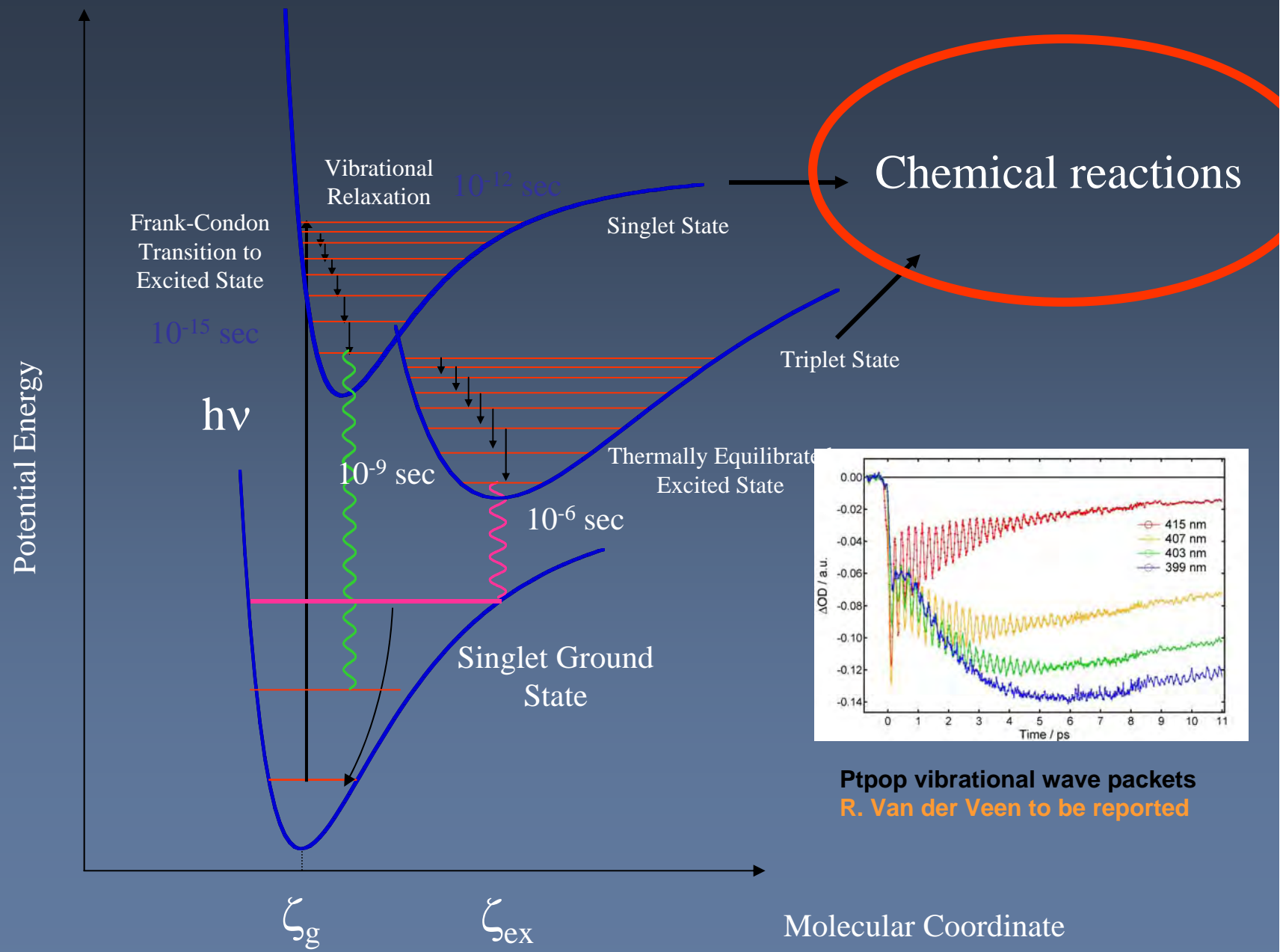
Rice and Gray 1983: **0.21 Å**

Solution (acetonitrile)

Leung et al 1999: **0.225 Å**

This Talk

- Photochemical mechanisms
and environmental factors
What can we learn on fs time scales?
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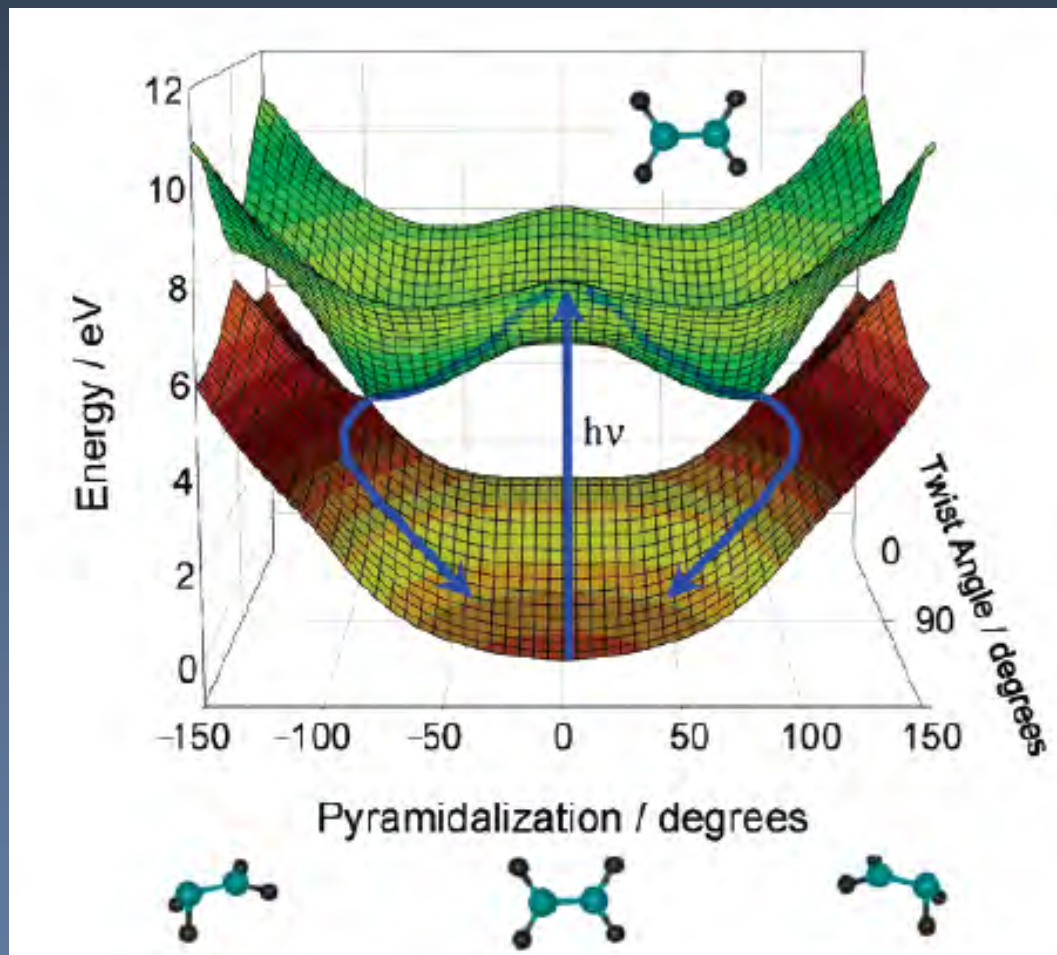


Ptppop vibrational wave packets
 R. Van der Veen to be reported

Excited state energy surfaces and conical intersections

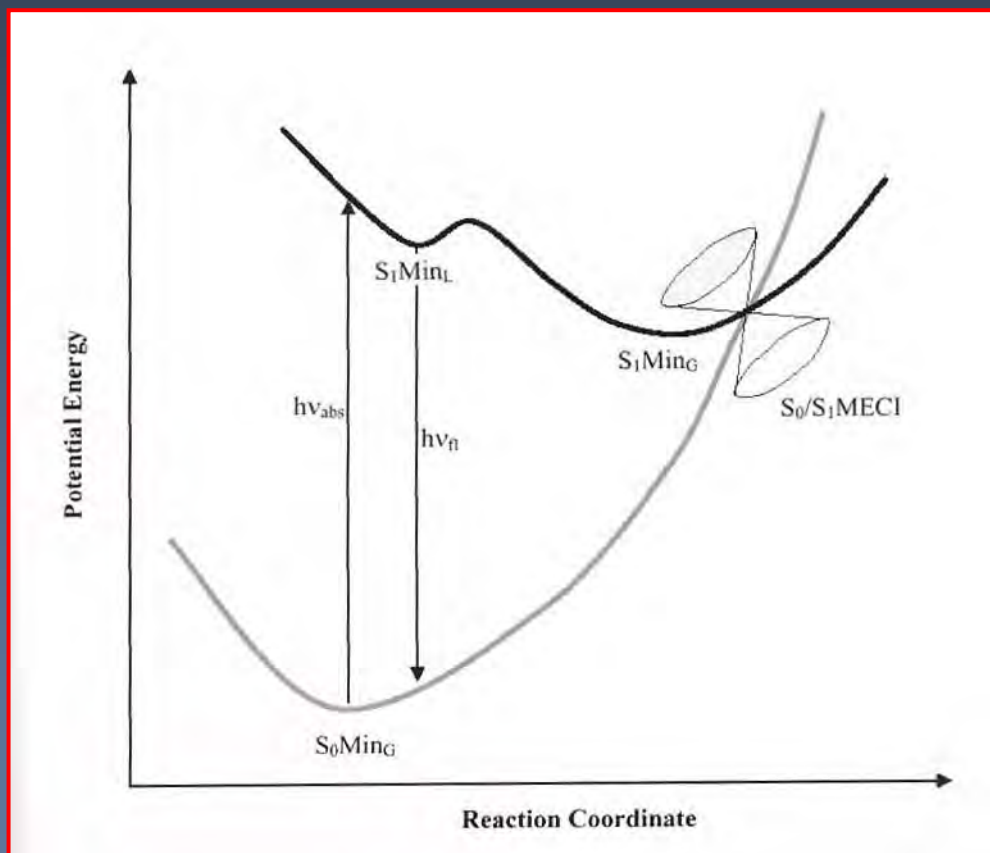
Isomerization of ethylene as a model for retinal cis-trans isomerization

- two coordinates: twist angle and pyramidalization (a simplification)
- 2 conical intersection, symmetric in this case, but not symmetric in general



T. J. Martinez, *Acc. Chem. Res.* 39, 119-126, 2006

Another look at the conical intersection : local minima on the S_1 surface



Dependence on the environment

Ethylene: lifetime of excited state 30 ± 15 fsec

Farmanara *et al.* Chem. Phys. Lett. **1998**, 288, 518-522.

calculated: 30 fsec (Martinez)

Rhodopsin:

bond $C_{11}-C_{12}$

200 fs

Bacteriorhodopsin

bond $C_{12}-C_{13}$

500 fs

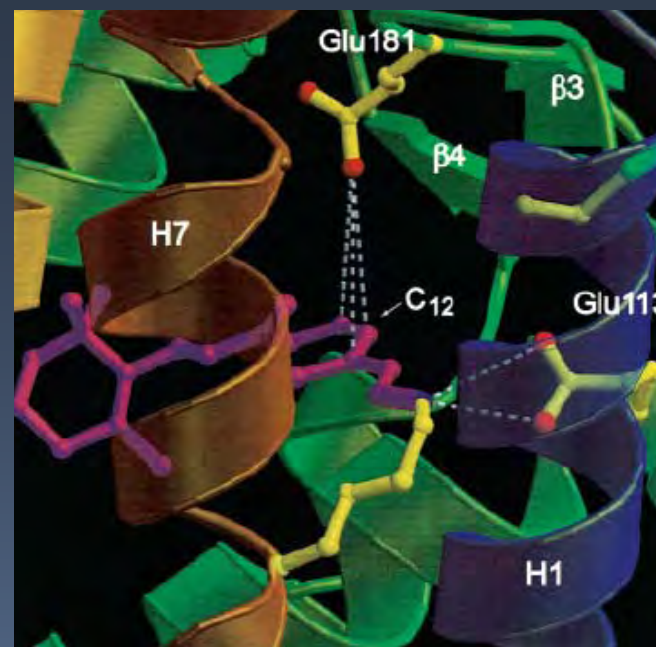
Retinal in solution

Isomerization not bond specific

2.5-10 ps

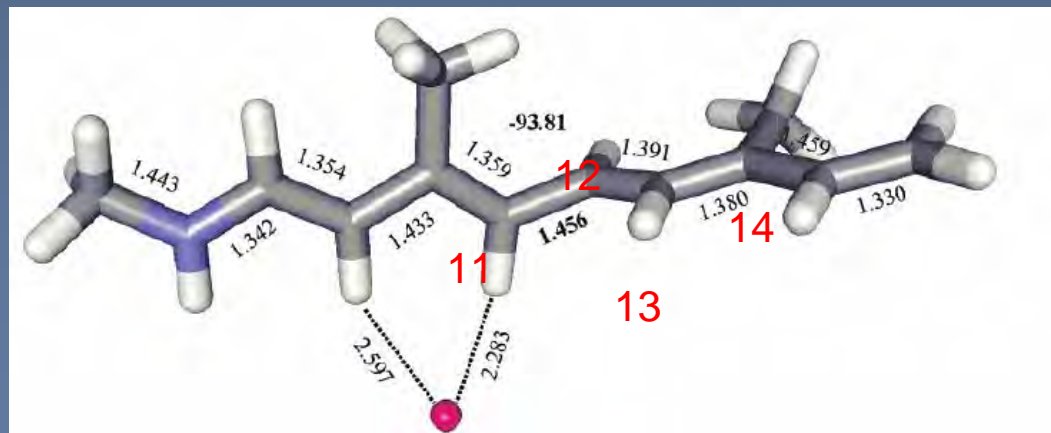
El-Sayed *et al.* J. Phys. Chem.

1996, 100, 18586-18591



From Yan *et al.* Biochemistry **2002**, 41, 3620-3627

calculated structure at conical intersection of retinal



Martinez, Acc. Chem. Res. 39, 119-126, 2006

Martinez, Acc. Chem. Res. 39, 119-126, 2006

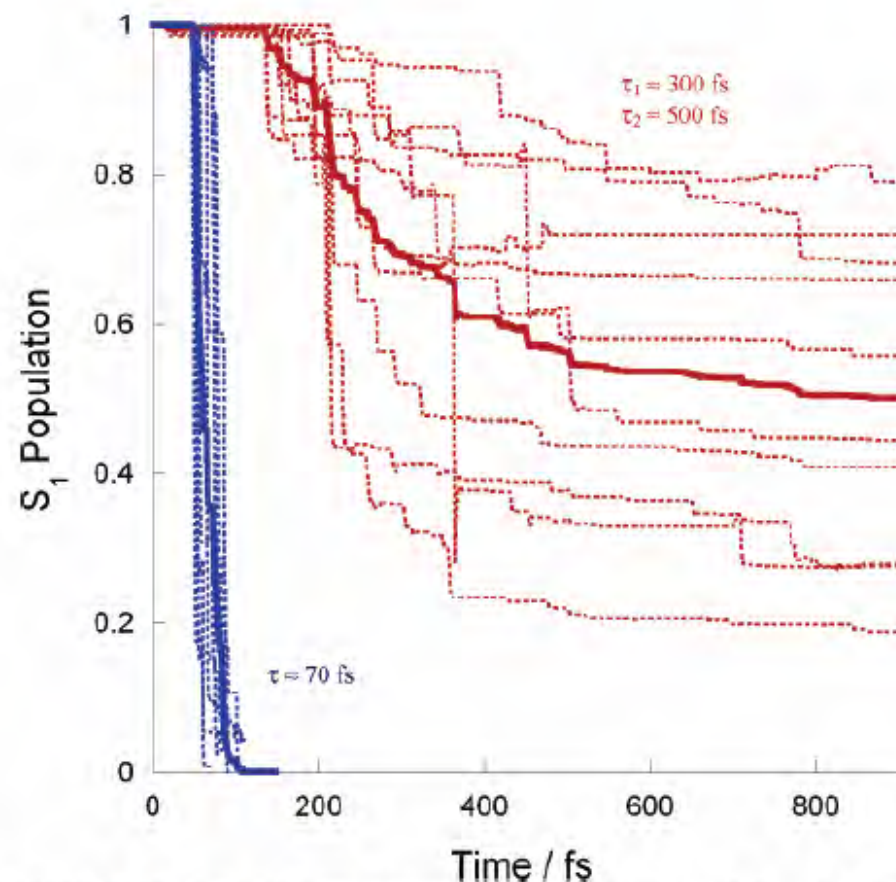


FIGURE 7. Excited-state population as a function of time for the neutral form of the GFP chromophore in vacuum (red) and micro-solvated aqueous (blue) environments. The dotted lines refer to individual runs, and the dark lines represent the averaged behavior. Aqueous solvation dramatically decreases the excited-state lifetime.

Two different salts of the $[\text{Pt}(\text{pop})_4]^{4+}$ ion

$\text{K}_2\text{MV}[\text{Pt}(\text{pop})_4]$: Lifetime at 17K

12 μs (ex.366nm)

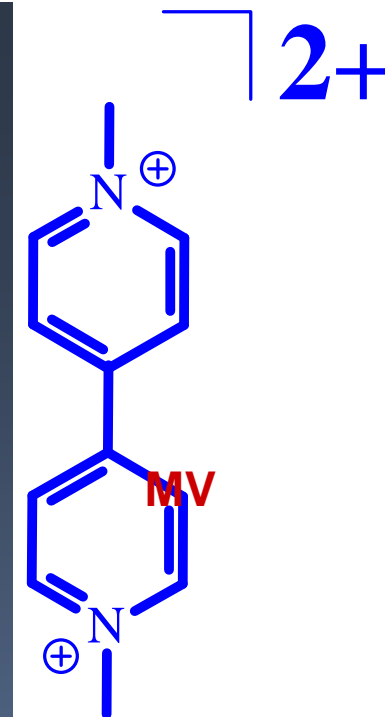
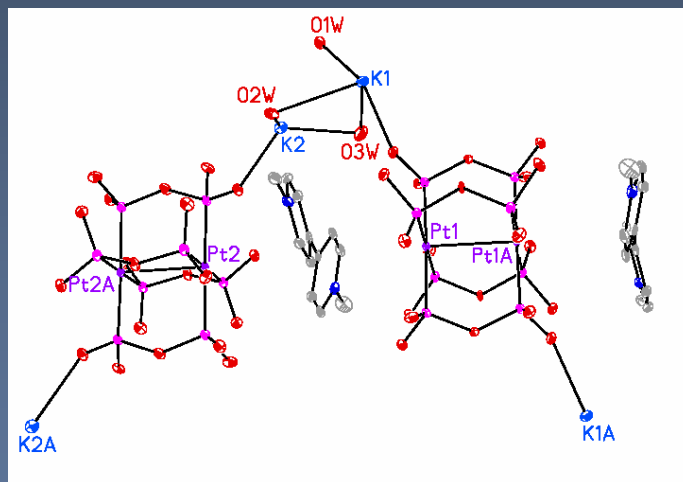
15 μs (ex.446nm)

$\text{MV}_2[\text{Pt}(\text{pop})_4]$:

no emission observed



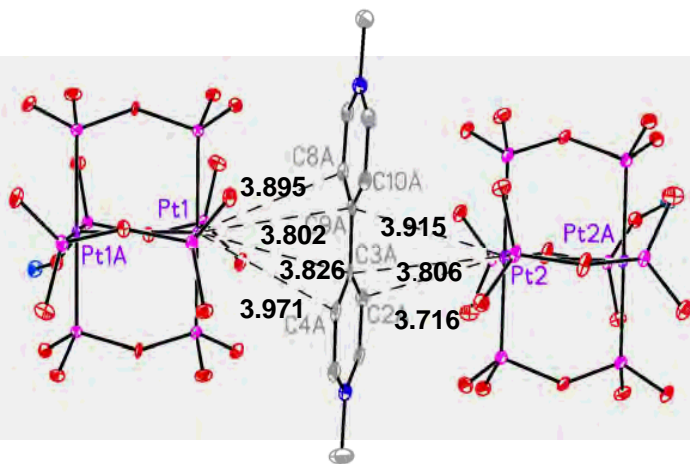
10 min



Structures of the 2 salts

$K_2(MV)Pt_{pop}$

17 μ s at 17K



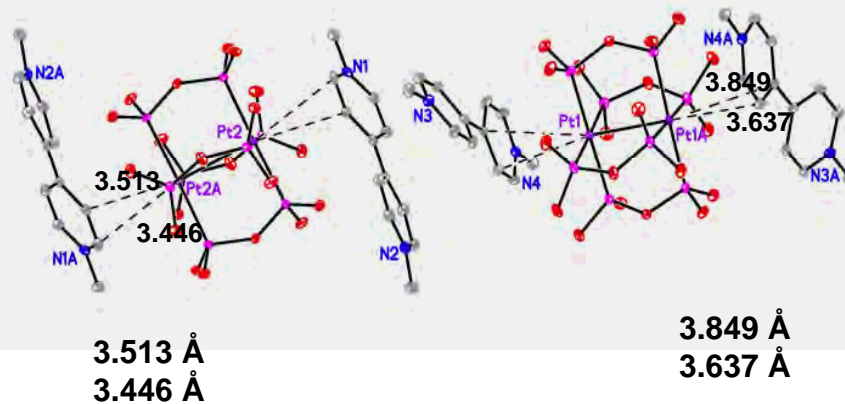
Distance from Pt:

3.895 Å
3.802 Å
3.826 Å
3.974 Å

3.915 Å
3.806 Å
3.716 Å

$(MV)_2Pt_{pop}$

no emission



3.513 Å
3.446 Å

3.849 Å
3.637 Å

This Talk

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How are we going to measure this?

Monochromatic (~0.3% bandwidth)

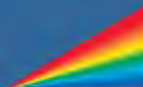
- 1) measure only a few reflections? Limited to special cases
- 2) Use of powder diffraction? Limited to simpler structures
- 3) Use of an array of nanocrystals in random orientation, using common-line method or topographic mapping to retrieve orientation,
- 4) Use of molecular beams for unimolecular reactions?

Laue (polychromatic continuum?)

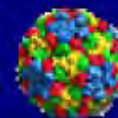
comparable in flux with third generation synchrotron sources
femtosecond resolution

because of lower flux, multiple shots may be possible

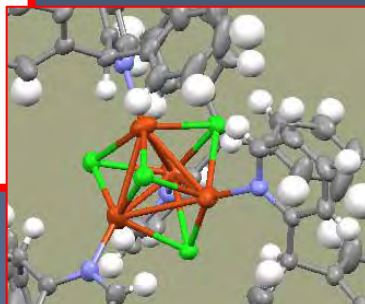
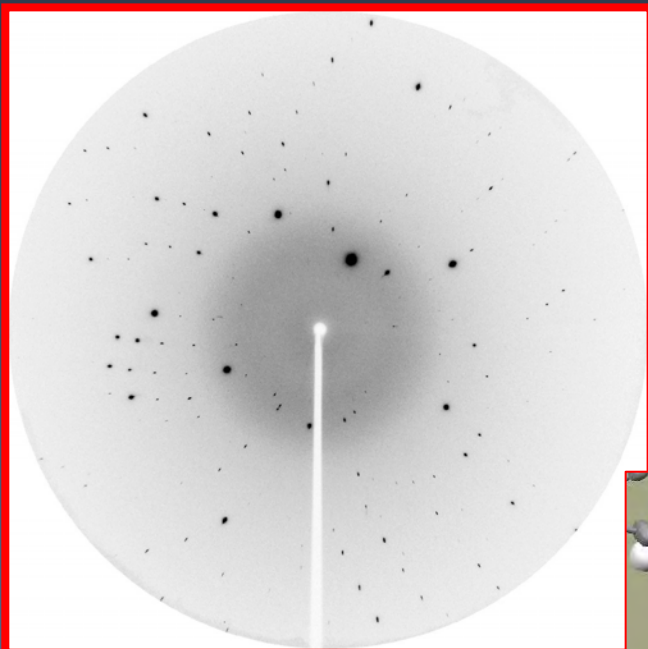
Single pulse Laue at APS



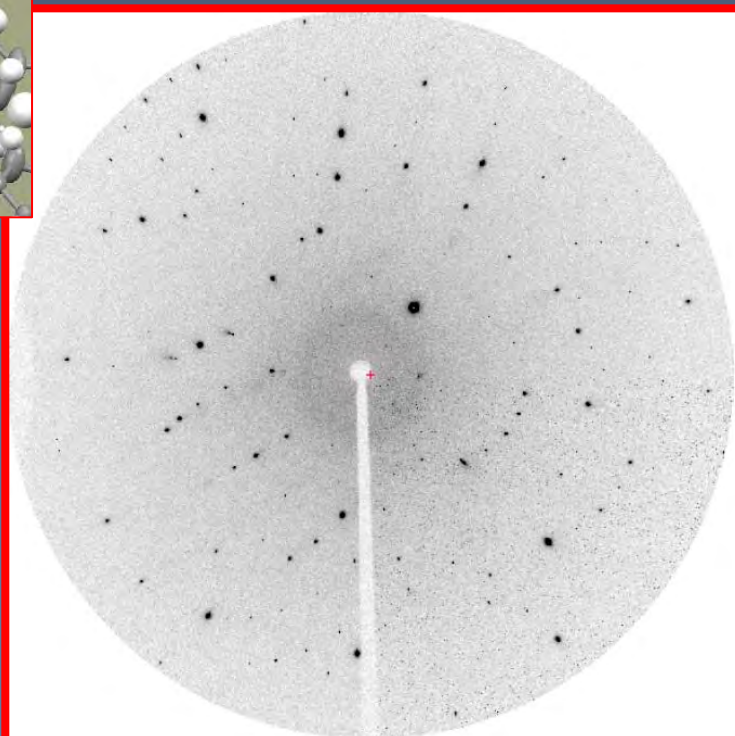
Advanced Photon Source
A U.S. Department of Energy, Office of Science,
Office of Basic Energy Sciences national synchrotron x-ray research facility



BioCARS
A Synchrotron Structural Biology Resource



70 ps diffraction
(Laue, APS 14-ID)



This Talk

- Final Remarks

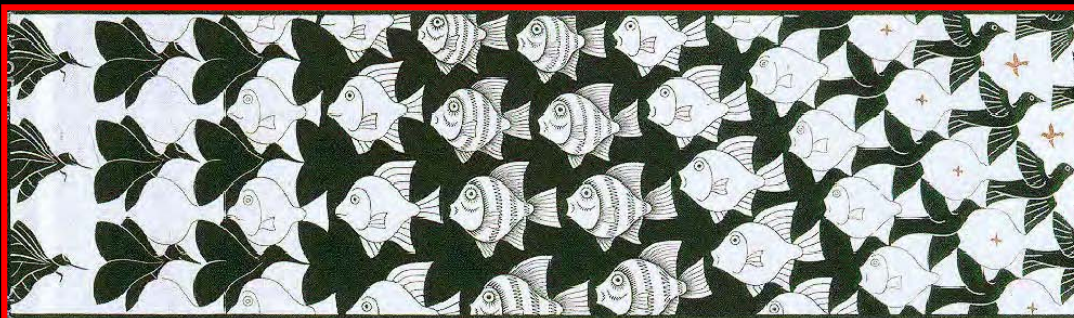
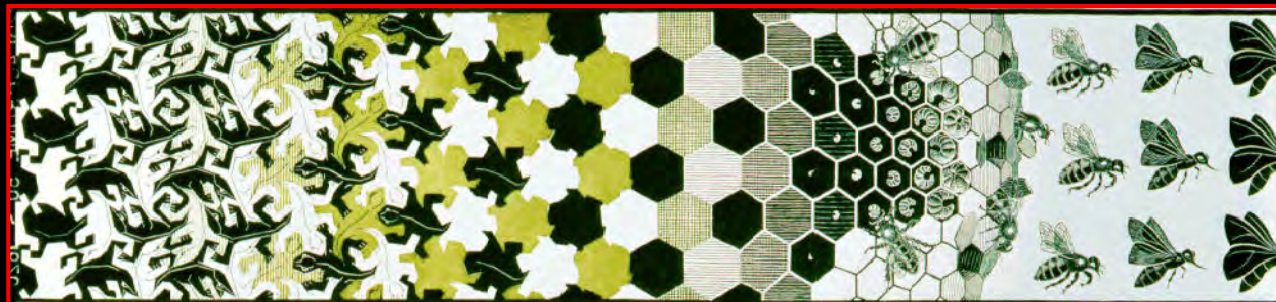
Final remarks

Femtosecond studies are essential for the understanding of reaction mechanism

Excited states and chemical reactions are environment-dependent

The mechanism measured may not be the crucial one

We can not hope to design chemical reactions unless we understand the intermediate structures



M.C. Escher
Metamorphose