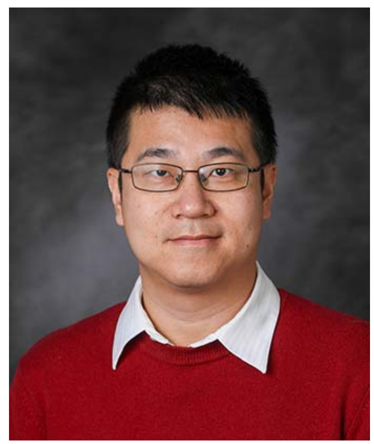
VISTA Talk

July 28, 2021

I. Self-assembly of peptide amphiphiles
II. Two-photon absorption with entangled photons

George C. Schatz
Northwestern University



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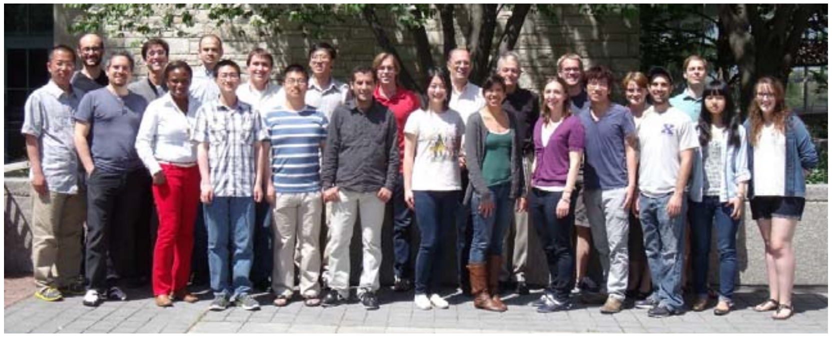
Tao's work as a postdoc (2012-2014) and thereafter

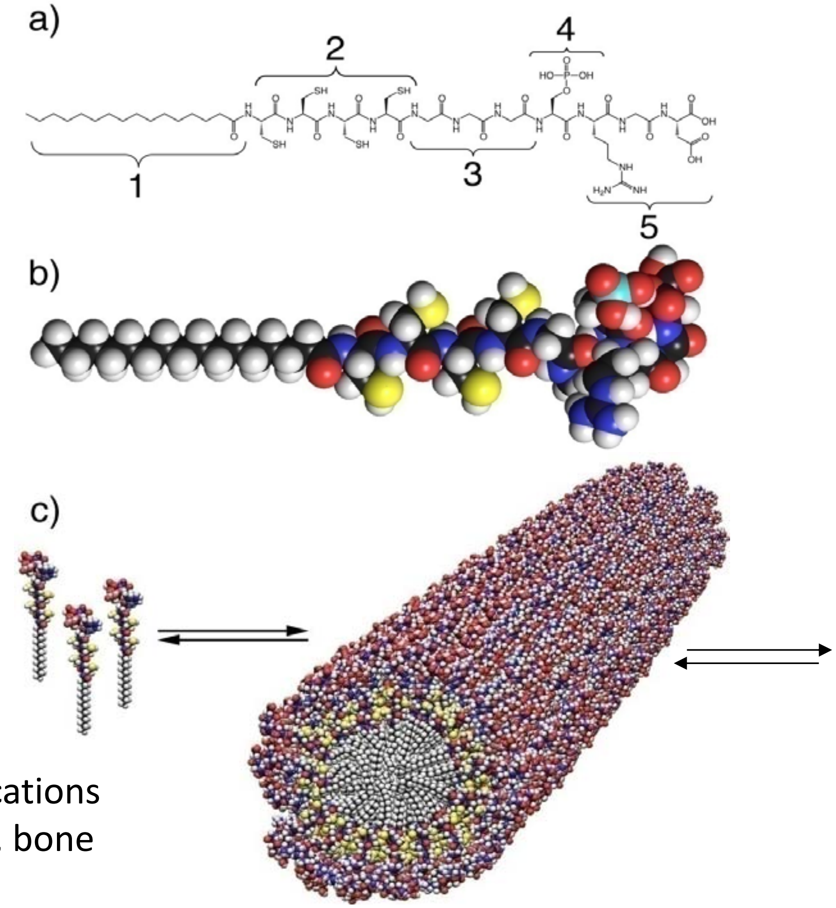


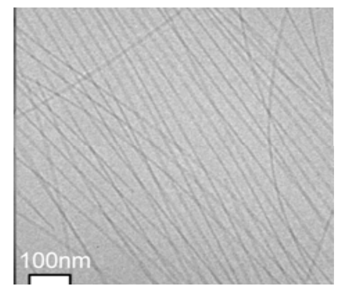
1)*Steered molecular dynamics studies of the potential of mean force for peptide amphiphile self-assembly into cylindrical nanofibers*, Tao Yu, One-Sun, Lee, George C. Schatz, J. Phys. Chem. A, 117. 9004-13 (2013)
2)*Free energy profile and mechanism of self-assembly of peptide amphiphiles based on a collective assembly coordinate*, Tao Yu, George C. Schatz, J. Phys. Chem. B, 117, 9004-9013(2013).
3)*Free-energy landscape for peptide amphiphile self-assembly: stepwise versus continuous assembly mechanisms*, Tao Yu, George C. Schatz, J. Phys. Chem. B, 117, 14059-14064 (2013).
4)*Molecular dynamics simulations and electronic excited state properties of a self-assembled peptide amphiphile nanofiber with metalloporphyrin arrays*, Tao Yu, One-Sun Lee and George C. Schatz, J. Phys Chem. A, 118, 8553-62 (2014).
5)*Energy landscapes and functions of supramolecular systems*, Faifan Tantakitti, Job Boekhoven, Xin Wang, Roman V. Kazantsev, Tao Yu, Jiahe Li, Ellen Zhuang, Roya Zandi, Julia H. Ortony, Christina J. Newcomb, Liam C. Palmer, Gajendra S. Shekhawat, Monic Olvera de la Cruz, George C. Schatz, Samuel I. Stupp, Nature Materials, 15, 469-477 (2016)
6)*Simultaneous covalent and noncovalent hybrid polymerizations*, Zhilin Yu, Faifan Tantakitti, Tao Yu, Liam C. Palmer, George C. Schatz, Samuel I. Stupp, Science 351, 497-502 (2016)
7)*A Mutation in Histone H2B Represents a New Class of Oncogenic Driver*, Richard L Bennett, Aditya Bele, Eliza C Small, Christine M Will, Behnam Nabet, Jon A Oyer, Xiaoxiao Huang, Rajarshi P Ghosh, Adrian T Grzybowski, Tao Yu, Qiao Zhang, Alberto Riva, Tanmay P Lele, George C Schatz, Neil L. Kelleher, Alexander J Ruthenburg, Jan Liphardt and Jonathan D Licht, Cancer Discovery, 9, 1438-51 (2019)

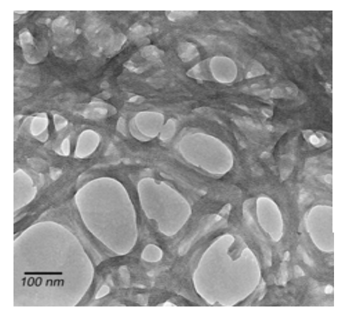
Self-Assembly of Peptide Amphiphiles

J.D. Hartgerink, E. Beniash, and S.I. Stupp, Science, **294**, 1605 (2001).

Sam Stupp







Fibers have applications in wound healing, bone growth, nerve regeneration, etc

Methods for describing the assembly of structures driven by hydrogen bonds and other weak interactions:

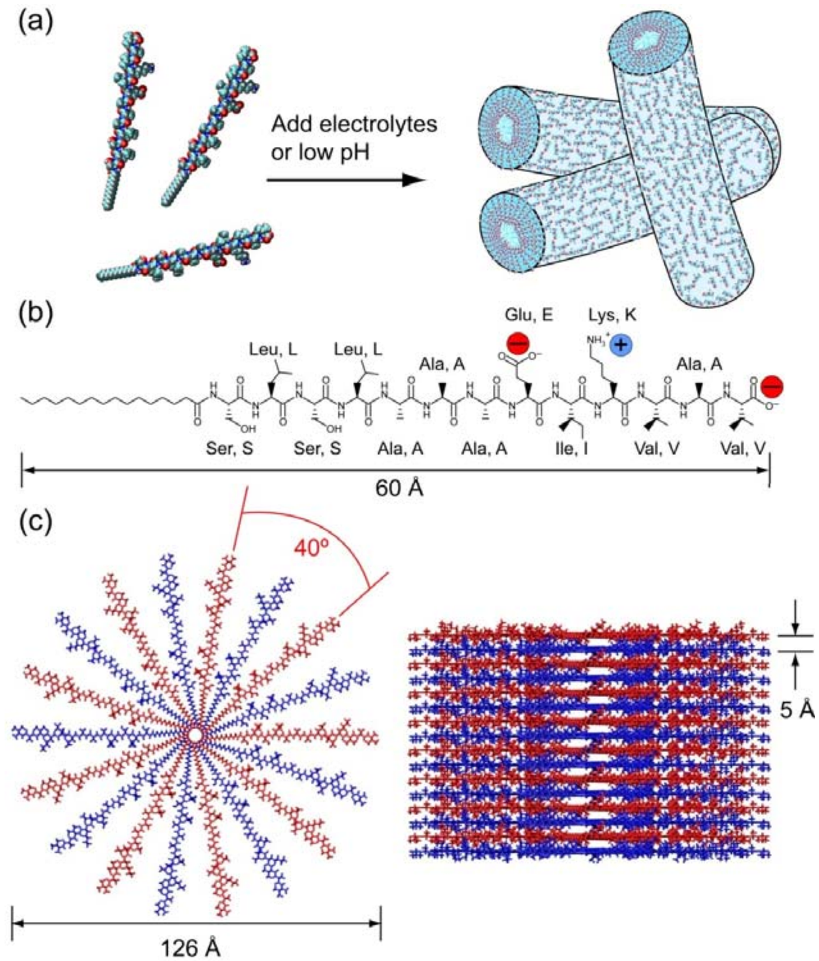
Monte Carlo, Molecular Dynamics, Molecular Mechanics

Atomistic, Coarse-grained force fields

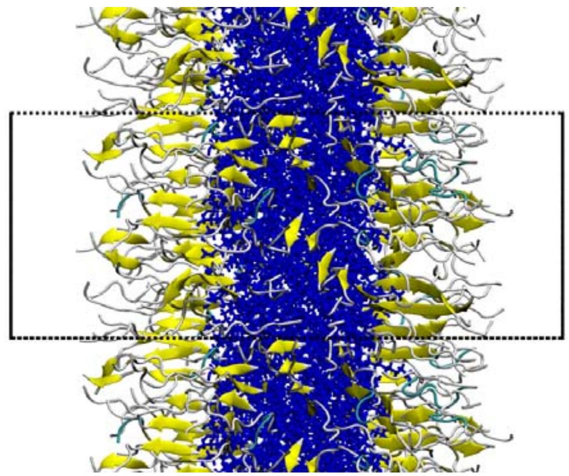
Structural Models and Self-Assembly Tricks

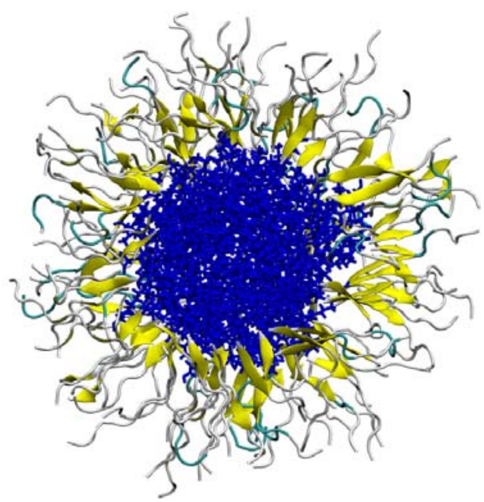
Atomistic Modeling with Seeded Structures

One-Sun Lee, Samuel I. Stupp and George C. Schatz, J. Am. Chem. Soc. 113, 3677-3683 (2011)



Self-assembly stabilizes after a 40 ns simulation

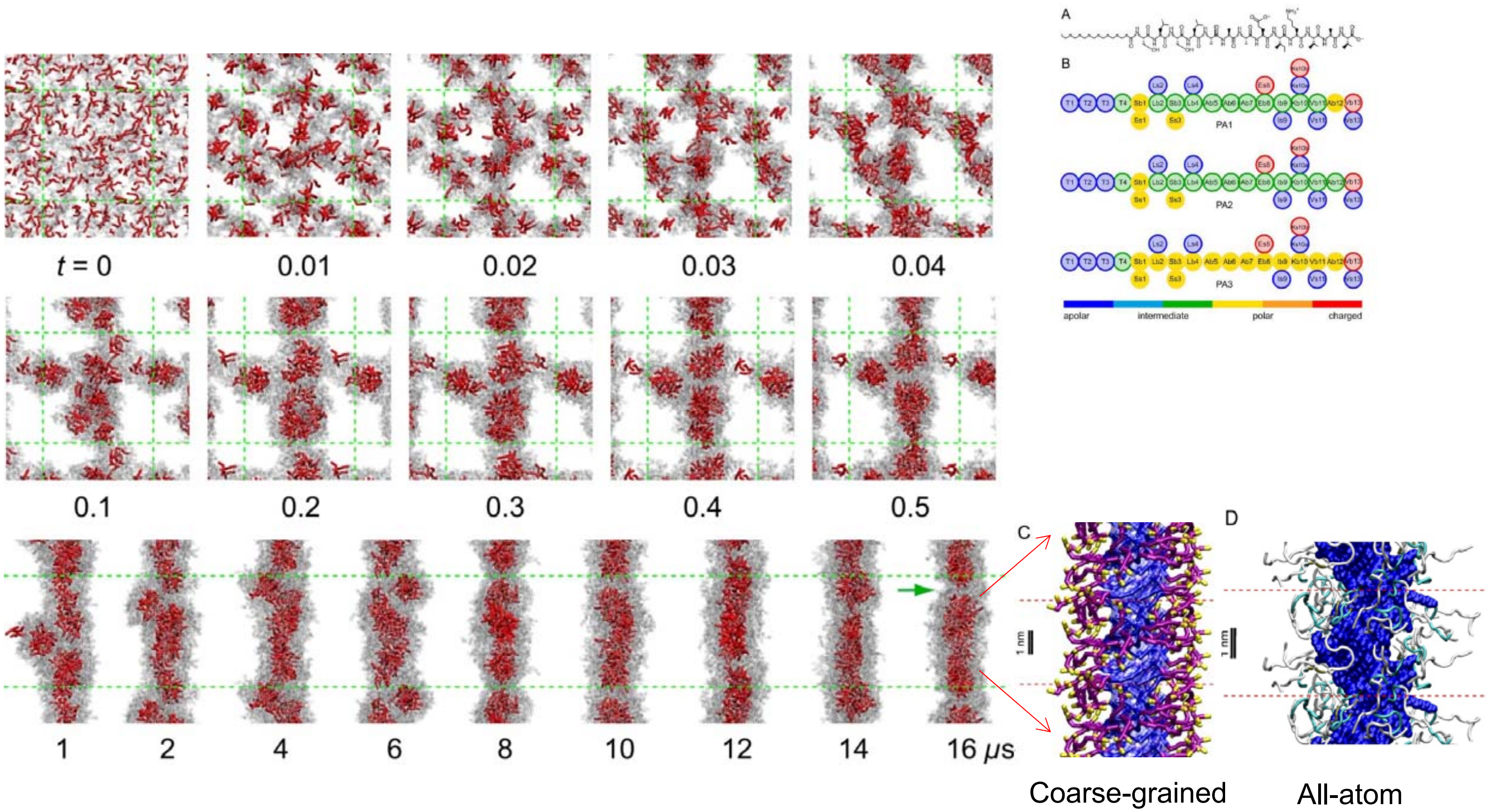




One-Sun Lee, Samuel I Stupp and George C. Schatz, J. Am. Chem. Soc. 113, 3677-3683 (2011)

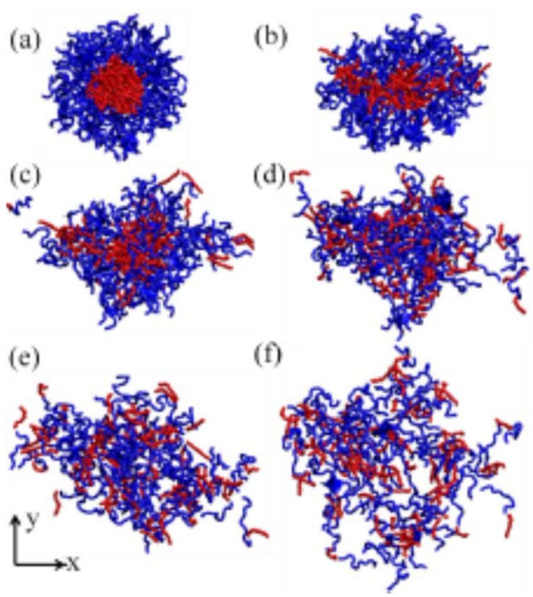
Aysenur Iscen and George C. Schatz 2017 EPL 119 38002

Coarse-grained models enable simulation of the complete assembly process

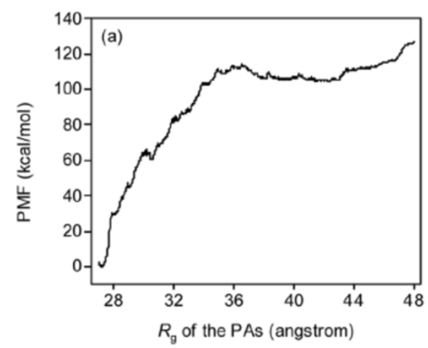


O.-S. Lee, V. Cho, G. C. Schatz, Nano Lett. 12, 4907-4913 (2012).

Self-assembly mechanism



Potential of mean force vs radius of gyration



Tao Yu, George C. Schatz, J. Phys. Chem. B, 117, 9004-9013(2013).

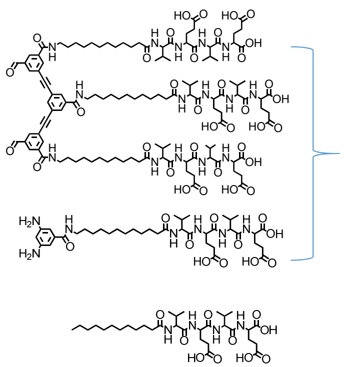
Simultaneous Covalent and Noncovalent Hybrid Polymerizations

Z. Yu, F. Tantakitti, T. Yu, L. C. Palmer, G. C. Schatz and S. I. Stupp, Science, 351, 497, 2016

1

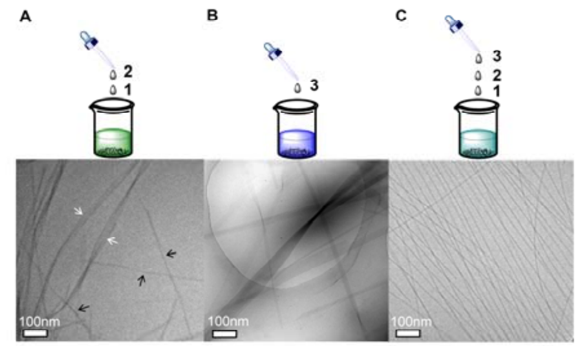
2

3

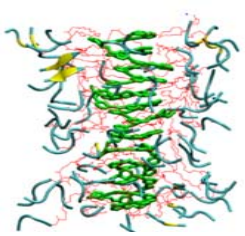


These two can be covalently linked, yielding (1+2) fibers

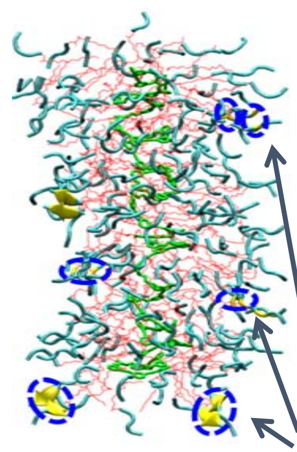
3 forms ribbons by itself, but can be added to (1+2) to make fibers



Theory confirms the structures, showing how beta sheets link (3) to (1+2)

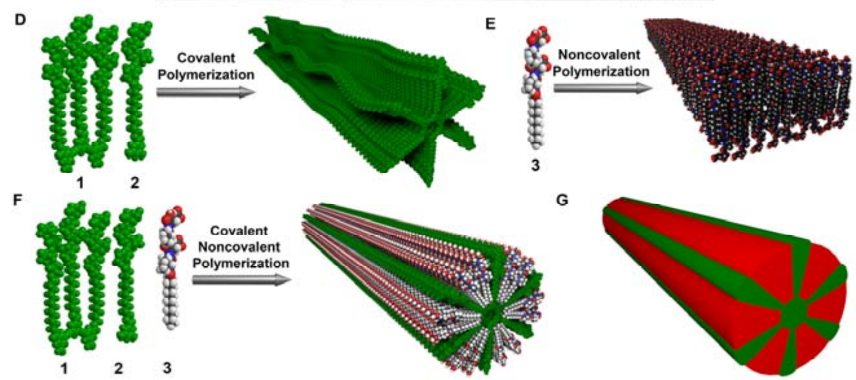


1+2



1+2+3

β sheets linking 3 to 1+2

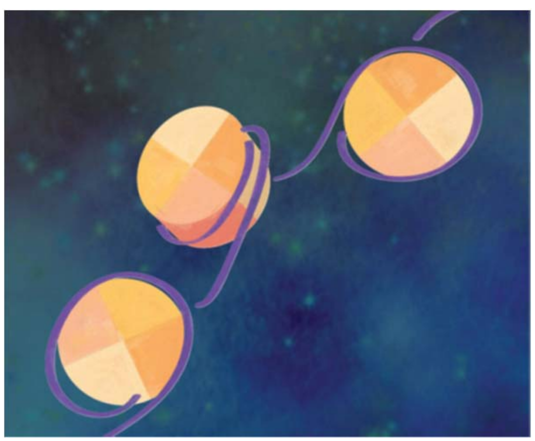


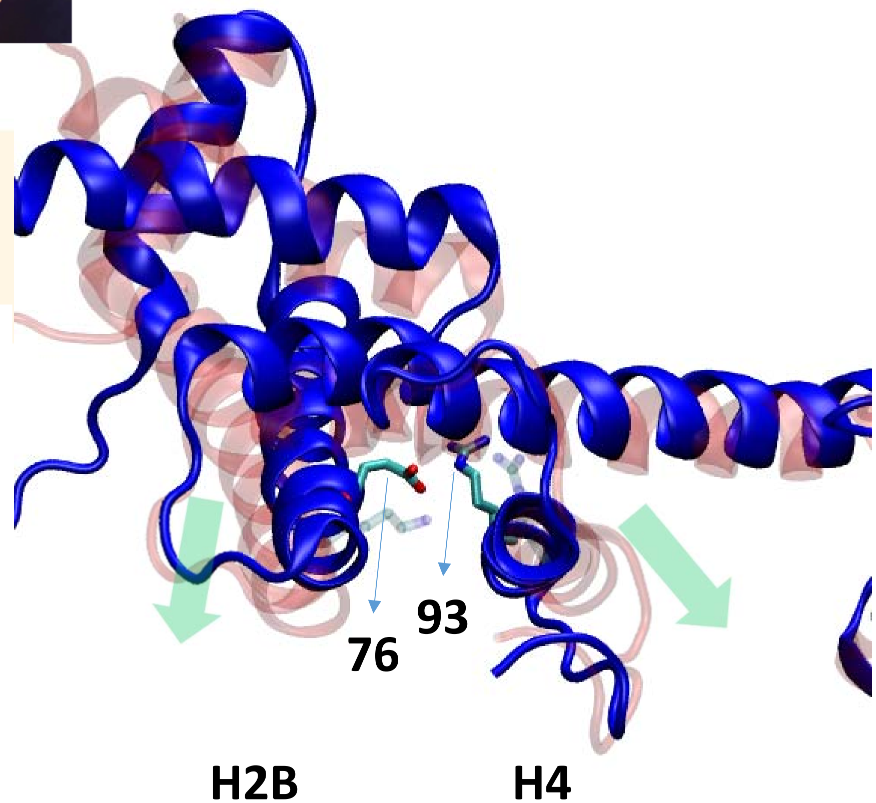
A Mutation in Histone H2B Represents a New Class of Oncogenic Driver

Richard L. Bennett[1], Aditya Bele[1], Eliza C. Small[2], Christine M. Will[2], Behnam Nabet[3], Jon A. Oyer[2], Xiaoxiao Huang[1,4], Rajarshi P. Ghosh[5], Adrian T. Grzybowski[6], Tao Yu[7], Qiao Zhang[8], Alberto Riva[9], Tanmay P. Lele[8], George C. Schatz[4], Neil L. Kelleher[4], Alexander J. Ruthenburg[6], Jan Liphardt[5], and Jonathan D. Licht[1]

Cancer Discovery, 9, 1438-51 (2019)

ABSTRACT By examination of the cancer genomics database, we identified a new set of mutations in core histones that frequently recur in cancer patient samples and are predicted to disrupt nucleosome stability. In support of this idea, we characterized a glutamate to lysine mutation of histone H2B at amino acid 76 (H2B-E76K), found particularly in bladder and head and neck cancers, that disrupts the interaction between H2B and H4.



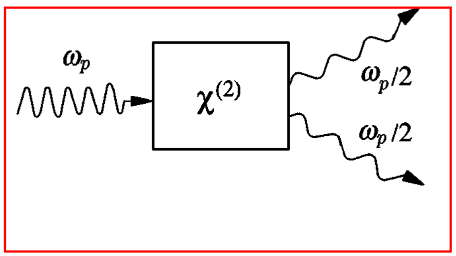


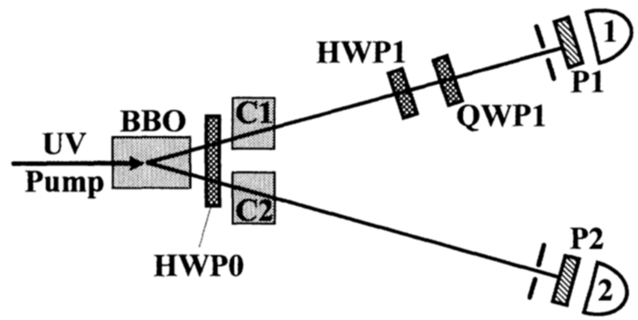
Entangled two-photon absorption

George C. Schatz
Northwestern University

Entangled photon sources

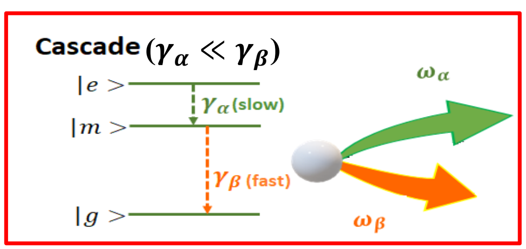
1. **Spontanous parametric down conversion** SPDC (nonlinear crystal produces two photons)



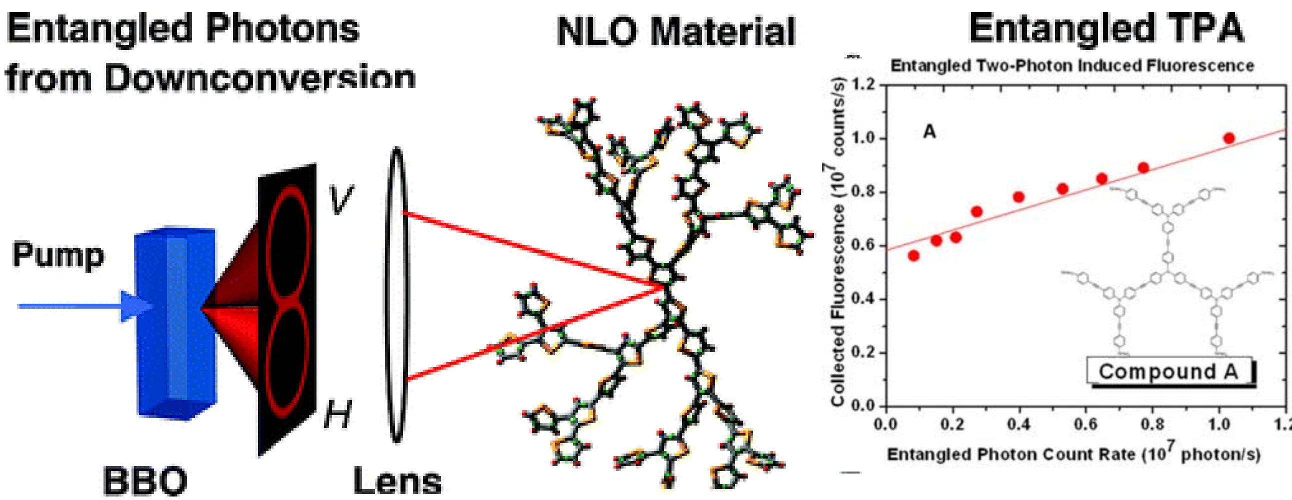


$$|\text{twin}\rangle = Nl \int\int d\omega_1\, d\omega_2 \exp\left[-\frac{(\omega_1 + \omega_2 - \omega_p)^2}{\Delta\omega_p^2}\right] \text{sinc}\left[\frac{l}{2\pi}(k_1 + k_2 - k_p)\right] |\omega_1, \omega_2\rangle.$$

2. **Quantum cascade** (emission by a doubly excited species)



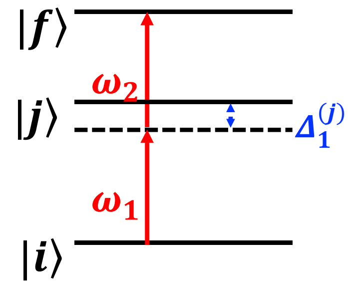
Entangled Two-photon Absorption (ETPA)



- ❑ Type II Spontaneous parametric down-conversion (SPDC) is used to generated entangled photon pairs ($\vec{\boldsymbol{p}}_1 \perp \vec{\boldsymbol{p}}_2$)
- ❑ Quadratic (Random TPA) vs Linear (ETPA) dependence on input flux

Goodson *et al. J. Am. Chem. Soc.* **2009**, *131*, 973-979;
Goodson, Mukamel, *J. Phys. Chem. Lett.* **2013**, *4*, 2046

Entangled and Unentangled two photon absorption



unentangled TPA rate: Rate = $\delta_R\, \Phi^2$ Φ^2 = square of flux ($cm^{-4}s^{-2}$)

Turns into a lineshape function g(ω) when factoring in final state density

TPA cross section:

$$\delta_R = 2\pi^3 \frac{(\hbar r_0 c)^2}{(\hbar\omega)^2}\delta\left(\frac{E_f - E_i - 2\hbar\omega}{\hbar}\right)\left[\left|\sum_j \frac{2<f|p_x|j><j|p_x|i>}{m(E_j - E_i - \hbar\omega - \hbar\kappa_j/2)}\right|^2\right]$$

$(r_0 = e^2/mc^2)$

ETPA rate: Rate = $\sigma_e\, \Phi$

ETPA cross section:

A_e: Entanglement Area

T_e: Entanglement Time

$$\sigma_e = \frac{\pi}{4A_eT_e}(2\pi)^2\frac{(r_0c)^2}{(\omega_1^0\omega_2^0)}\delta\left(\frac{E_f - E_i - 2\hbar\omega}{\hbar}\right)$$

$$\times\left|\sum_j\left\{\frac{<f|p_{x,2}|j><j|p_{x,1}|i>}{m(E_j - E_i - \hbar\omega_1^0 - \hbar\kappa_j/2)}(1 - e^{-iT_e(E_j - E_i - \hbar\omega_1^0)/\hbar - T_e\kappa_j/2}) + \frac{<f|p_{x,1}|j><j|p_{x,2}|i>}{m(E_j - E_i - \hbar\omega_2^0 - \hbar\kappa_j/2)}(1 - e^{-iT_e(E_j - E_i - \hbar\omega_2^0)/\hbar - T_e\kappa_j/2})\right\}\right|^2$$

Teich *et al. Phys. Rev. Lett.* **1996**, *78*(9), 1679-1682

Relationship between TPA and ETPA

TPA cross section:

$$\delta_R = 2\pi^3 \frac{(\hbar r_0 c)^2}{(\hbar\omega)^2}\delta\left(\frac{E_f - E_i - 2\hbar\omega}{\hbar}\right)\left[\left|\sum_j \frac{2 < f\,|\,p_x\,|\,j >< j\,|\,p_x\,|\,i >}{m(E_j - E_i - \hbar\omega - \hbar\kappa_j/2)}\right|^2\right]$$

ETPA rate:

$$\sigma_e = \frac{\pi}{\boxed{4A_eT_e}}(2\pi)^2\frac{(r_0c)^2}{(\omega_1^0\omega_2^0)}\delta\left(\frac{E_f - E_i - 2\hbar\omega_p}{\hbar}\right)$$
$$\times\left|\sum_j\left\{\frac{< f\,|\,p_{x,2}\,|\,j >< j\,|\,p_{x,1}\,|\,i >}{m(E_j - E_i - \hbar\omega_1^0 - \hbar\kappa_j/2)}(1\boxed{- e^{-iT_e(E_j - E_i - \hbar\omega_1^0)/\hbar - T_e\kappa_j/2}}) + \frac{< f\,|\,p_{x,1}\,|\,j >< j\,|\,p_{x,2}\,|\,i >}{m(E_j - E_i - \hbar\omega_2^0 - \hbar\kappa_j/2)}(1\boxed{- e^{-iT_e(E_j - E_i - \hbar\omega_2^0)/\hbar - T_e\kappa_j/2}})\right\}\right|^2$$

If you ignore the oscillatory terms, then taking the ratio of these equations gives:

$$\sigma_e = \frac{\delta_R}{2T_eA_e}$$

This means that ETPA is like TPA with a flux $\Phi = 1/(2T_eA_e) = 5\text{x}10^{18}$ photons/cm^2/s for reasonable estimates of T_eA_e

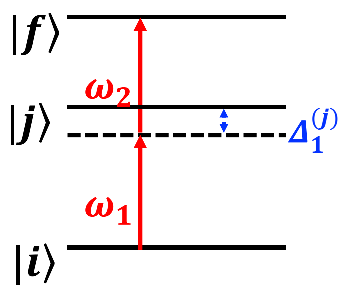
ETPA Cross-section

SPDC sources have been used to study entangled two-photon absorption, leading to cross sections that are many orders of magnitude larger than for TPA.

$$\sigma_e = \frac{\pi}{4A_eT_e}\omega_1^0\omega_2^0\delta(\epsilon_f - \epsilon_i - \omega_1^0 - \omega_2^0)$$

Goodson, Mukamel J. Phys. Chem. Lett. **2013**, *4*, 2046

$$\times \left| \sum_j \left[D_{21}^{(j)} \frac{1-\exp[-iT_e\Delta_1^{(j)} - T_e\kappa_j/2]}{\Delta_1^{(j)} - i\kappa_j/2} + D_{12}^{(j)} \frac{1-\exp[-iT_e\Delta_2^{(j)} - T_e\kappa_j/2]}{\Delta_2^{(j)} - i\kappa_j/2} \right] \right|^2$$



$\boldsymbol{D_{kl}^{(j)} = \langle f|\mu_k|j\rangle\langle j|\mu_l|i\rangle}$ **(transition matrix element)**

$\omega_1 = \omega_2 = \omega_p/2$ (signal and idler photon energies)

$\Delta_k^{(j)} = \varepsilon_j - \varepsilon_i - \omega_k$ (energy mismatch)

κ_j: Linewidth of state *j*

These values are calculated with 2nd linear response TDDFT (SLR-TDDFT)

Martin A. Mosquera, Lin X. Chen, Mark A. Ratner, George C. Schatz, J. Chem. Phys. 144, 204105/1-11, (2016).

Problem with reported values of σ_e and δ_R given the "experimental parameters" T_e and A_e

For spdc, previous estimates of T_e are usually about 0.1 ps, corresponding to the time it takes photons to traverse the BBO crystal.

A_e has been estimated as 10^{-6} cm^2, as determined by the 10 µm diameter of the beam that irradiates the BBO crystal.

However if $\sigma_e = 10^{-18}$ cm^2 (typical) and $\delta_R = 100$ GM (x10^{-50} cm^4 s)=10^{-48} cm^4 s

and
$$A_e = \frac{\delta_R}{2\sigma_e T_e}$$

Then this predicts $A_e = 10^{-48} /(10^{-13}\ 10^{-18}) = 10^{-17}$ cm^2

Ouch!, off by 10^{11}

Problem can be fixed by realizing that the Dirac Delta functions in the TPA and ETPA expressions don't refer to the same state density

In this case, the delta functions become different lineshape functions:

$$\delta(2\omega - \omega_0) \rightarrow g_R \quad \text{TPA}$$
$$\delta(2\omega - \omega_0) \rightarrow g_e \quad \text{ETPA}$$

that describe the density of states for entangled (E) and unentangled (R) states of the molecule in the presence of the radiation field.

If the lineshape is Lorentzian:

$$g_{e,R} = \frac{1}{\pi} \frac{\Gamma_{e,R}}{(2\omega - \omega_0)^2 + \Gamma_{e,R}{}^2}$$

where $\Gamma_{e,R}$ is the HWHM of the lineshape for unentangled and entangled absorption. Typically it is only the peak cross section that is studied, in which case

$$g_{e,R} = \frac{1}{\pi \Gamma_{e,R}} = \frac{2}{\pi} \tau$$

Calculating TPA (unentangled cross sections)

There are many papers but a recent paper that provides exhaustive details is:

CrossMark

Cite this: *Phys. Chem. Chem. Phys.*, 2015, **17**, 19306

Benchmarking two-photon absorption cross sections: performance of CC2 and CAM-B3LYP

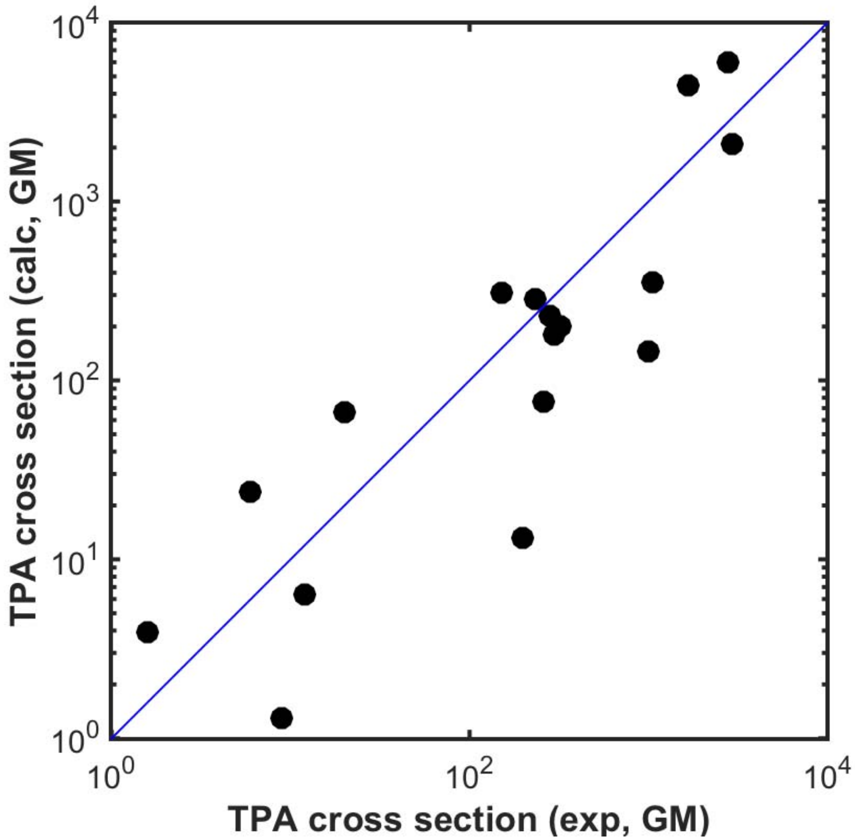
Maarten T. P. Beerepoot,*[a] Daniel H. Friese,[a] Nanna H. List,[b] Jacob Kongsted[b] and Kenneth Ruud[a]

$$\sigma^{\mathrm{TPA}} = \frac{4\pi^3 \alpha a_0^{\,5} \omega^2}{15c} \langle \delta^{\mathrm{TPA}} \rangle g(2\omega, \omega_0, \Gamma). \qquad \langle \delta^{\mathrm{TPA}} \rangle = \frac{1}{30} \sum_{ab} (F S_{aa} \bar{S}_{bb} + G S_{ab} \bar{S}_{ab} + H S_{ab} \bar{S}_{ba}),$$

$$S^{if}_{ab}(\omega_1, \omega_2) = \frac{1}{\hbar} \sum_{n \neq i} \left\{ \frac{\langle i|\mu_a|n\rangle \langle n|\bar{\mu}_b|f\rangle}{\omega_{ni} - \omega_1} + \frac{\langle i|\mu_b|n\rangle \langle n|\bar{\mu}_a|f\rangle}{\omega_{ni} - \omega_2} \right\}$$

The broadening effects are different for each excited state,[26] which can also be taken into account in theoretical work.[30,32,36,39] What is usually done, however, is choosing a single empirical parameter for Γ, often chosen to be 0.1 eV,[13,14,18,21,22,28,29,37,38]

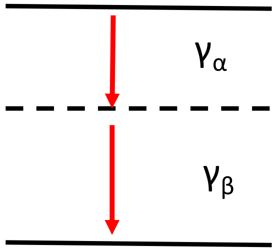
Our calculations (width = 0.1 eV) give results that are consistent with a factor of 10 variation between theory and expt for TPA



	exp, GM	calc, GM
6-Thiophene	6	24
18-Thiophene	230	288
ZnTPP	20	66
T161B	280	228
T161D	1040	358
bisstyrylbenzene	300	182
Bisannulene	150	305
Triannulene	1650	4446
Tetraannulene	2960	2105
Flavin Mononucleotide	1.6	3.9
R6G	9	1.3
stilbene1	12	6.3
stilbene2	200	13
stilbene3	995	144
stilbene12	260	76
stilbene13	320	199
dibenzoheptazethrene	2800	5959

What is the width or lifetime that is relevant to ETPA?

If only radiative effects are important, then we need the *radiative* lifetime of the two photon state. This can be calculated if we know the excited state properties (energies and transition moments to lower state). Typically it leads to lifetimes of μs to ms that are dominated by the lifetime for transition to the dominant intermediate state ($\Gamma = \gamma_\alpha$).



$$\tau_r = \left[\sum_{j<f} \frac{4}{3\hbar}\left(\frac{|\omega_{jf}|}{c}\right)^3 |\mu_{jf}|^2\right]^{-1}$$

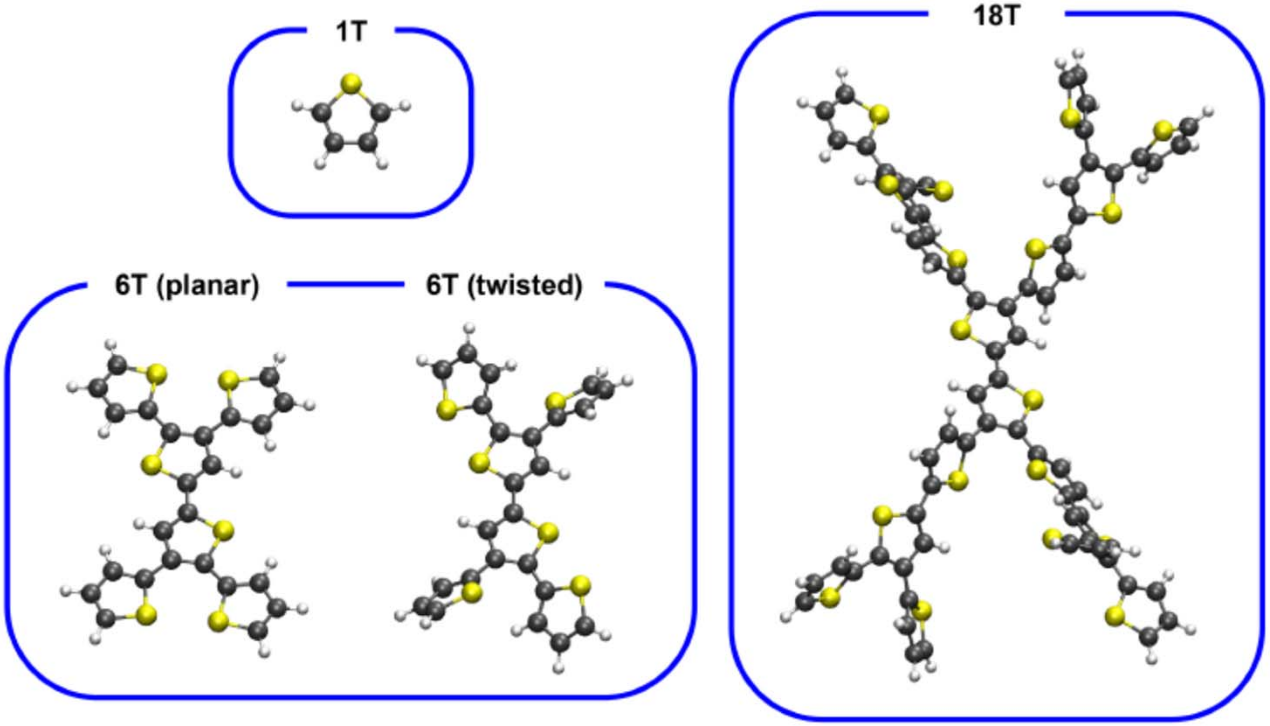
Further, if $\gamma_\alpha << \gamma_\beta$, photon is highly entangled, with a big Schmidt number.

Criticisms:
1. Assumes that entangled and unentangled states are not coupled. Are there proofs of this? There are theorems related to entanglement monogamy/faithfulness. Also, there are experiments (see later)
2. Only considers radiative contribution
3. Not clear that the two photon lifetime is measureable

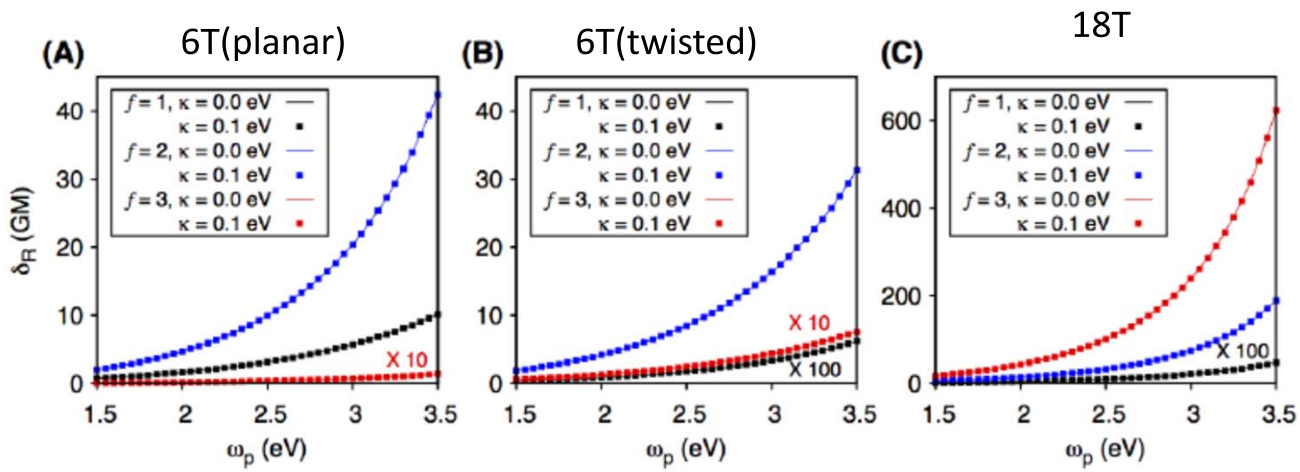
"geometrically faithful" entanglements quantitatively capture the fact that entangled states are very different than unentangled states.

Application of ETPA theory that uses SLR to calculate cross section including for radiative lifetime.

Thiophene dendrimers



Calculated TPA cross sections



Molecule	Experiment[20] δ_R $(10^{-50}$ cm^4 s)	Theory f	Theory δ_R $(10^{-50}$ cm^4 s)
6T (planar)	6	ES2	24
6T (twisted)		ES2	19
18T	230	ES2	90
		ES3	288

Two possible choices of the 2-photon excited state

G. Kang, K. Avanaki, M. Mosquera, R. K. Burdick, J. Monsalve, T. Goodson, G. Schatz, JACS142, 10446-10458 (2020).

Goodson *et al. J. Am. Chem. Soc.* 131, 3, **2009**

ETPA cross sections

Molecule	Experiment[20]	Theory			
	σ_e (10^{-19} cm^2)	f	σ_e (10^{-19} cm^2)	g_e (μs)	γ_f/γ_1
6T (planar)	1.3	ES2	1.7	988	6×10^{-4}
6T (twisted)		ES2	0.18	175	3×10^{-3}
18T	7.1	ES2	5.3	853	6×10^{-4}
		ES3	1.2	84	6×10^{-3}

Goodson *et al. J. Am. Chem. Soc.* 131, 3, **2009**

G. Kang, K. Avanaki, M. Mosquera, R. K. Burdick, J. Monsalve, T. Goodson, G. Schatz, JACS142, 10446-10458 (2020).

Conclusions

1. We can calculate TPA cross sections that are good to a factor of 10 using 0.1 eV for the width

2. ETPA cross sections are systematically shifted by a factor of ~10, and then the factor of 10 uncertainty also applies.