Investigating the Role of Entanglement in the Avian Compass

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Objective

- Understand the role of quantum coherence and entanglement in the biological compass system.

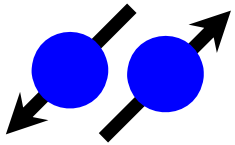
Magnetite Receptors

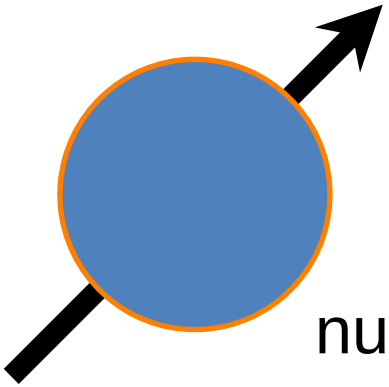
Induction Loops

Radical Pair Mechanism

The RPM model:

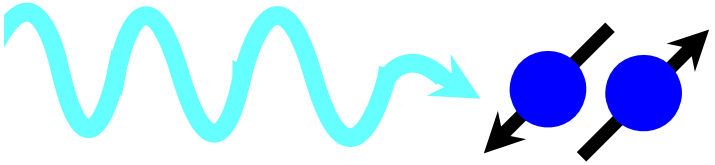
antiparallel electron pair

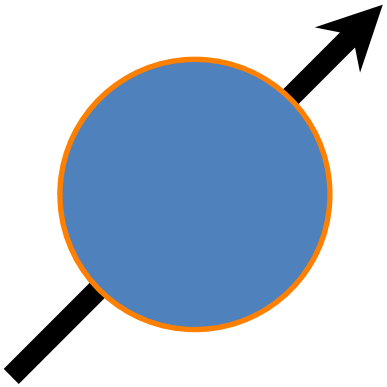


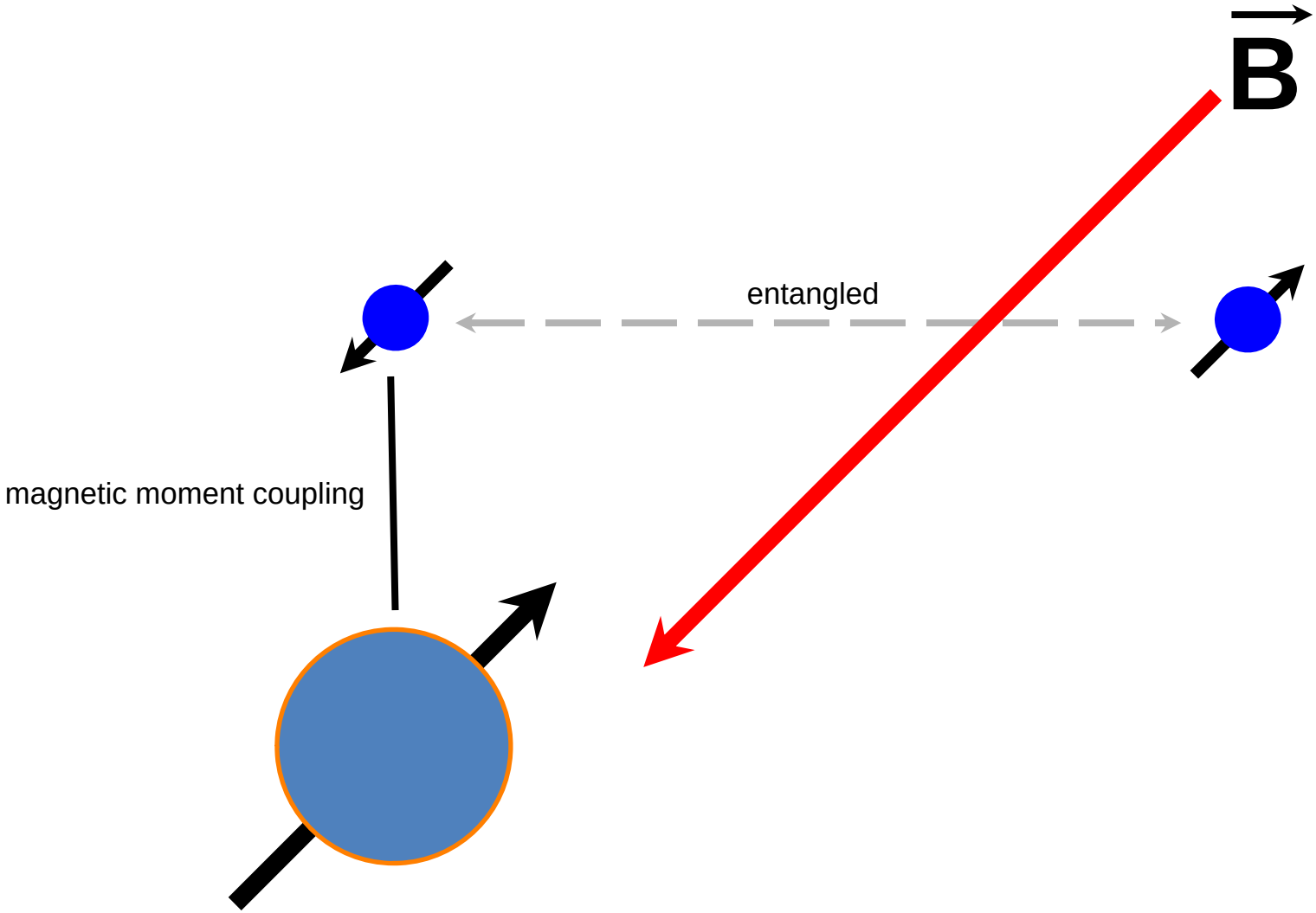


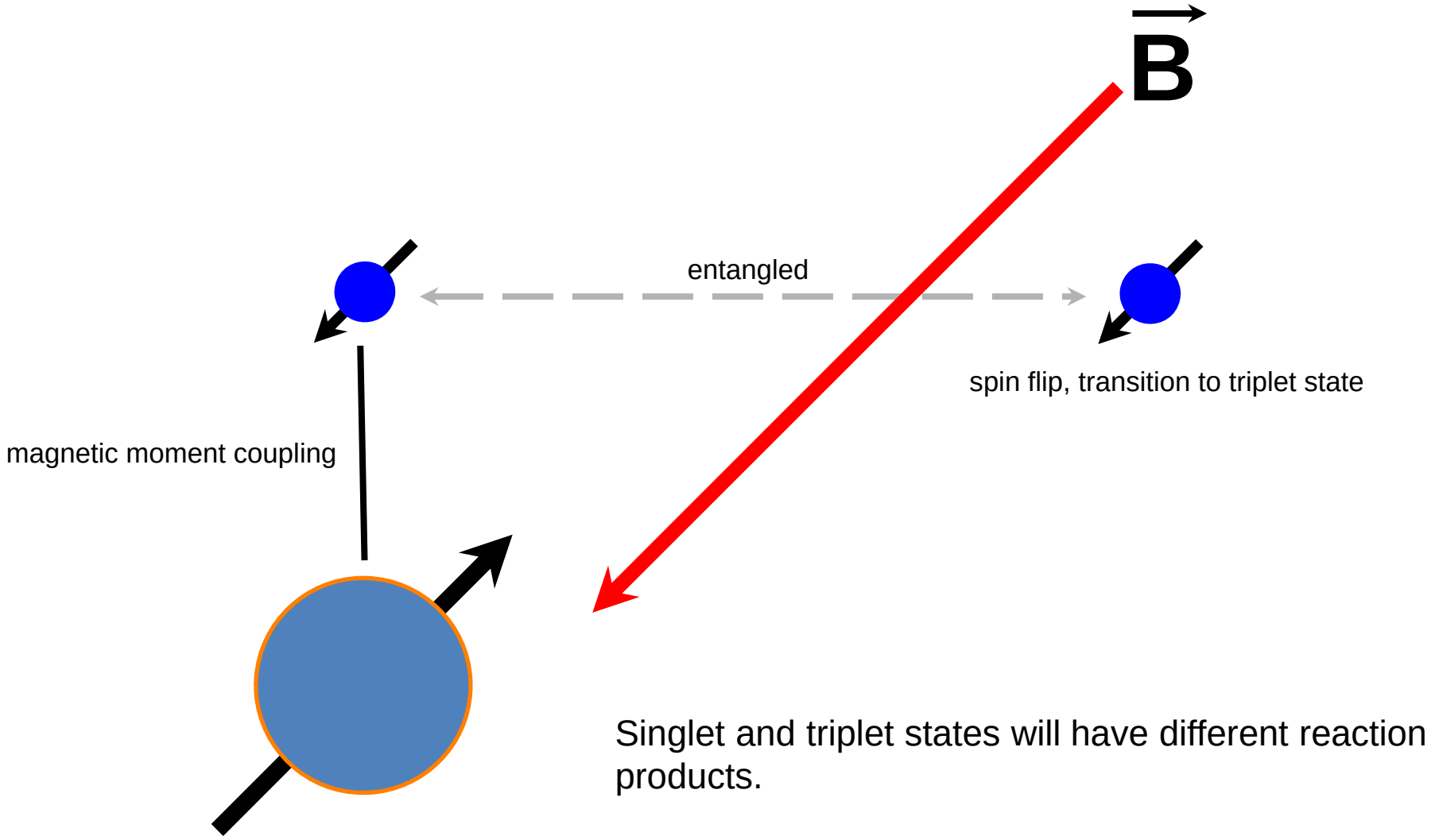
nuclear spin

blue photon



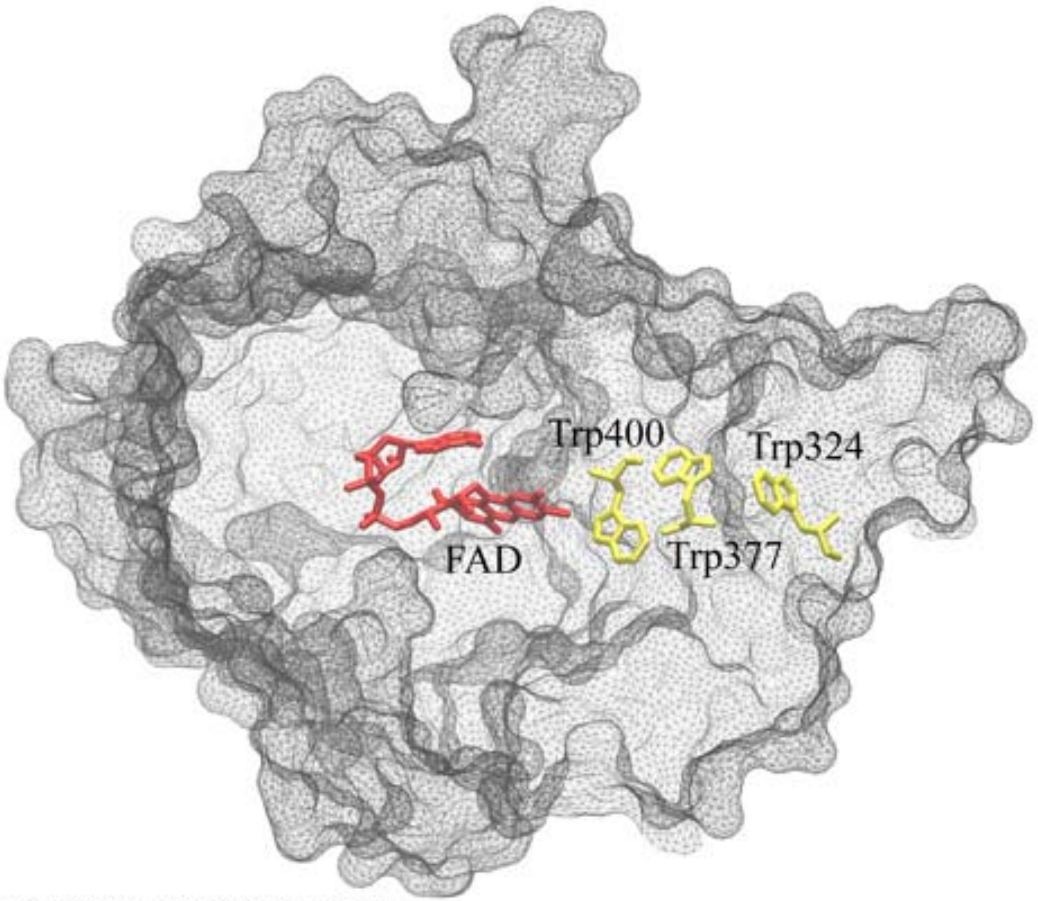



$\vec{B}$
entangled
magnetic moment coupling



Singlet and triplet states will have different reaction products.

Cryptochrome Molecule



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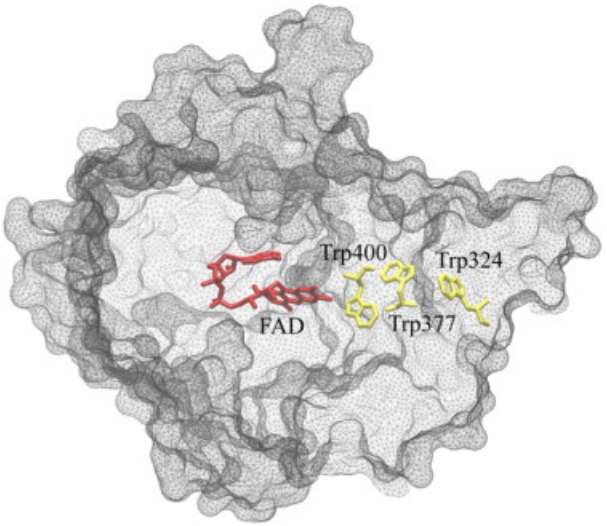
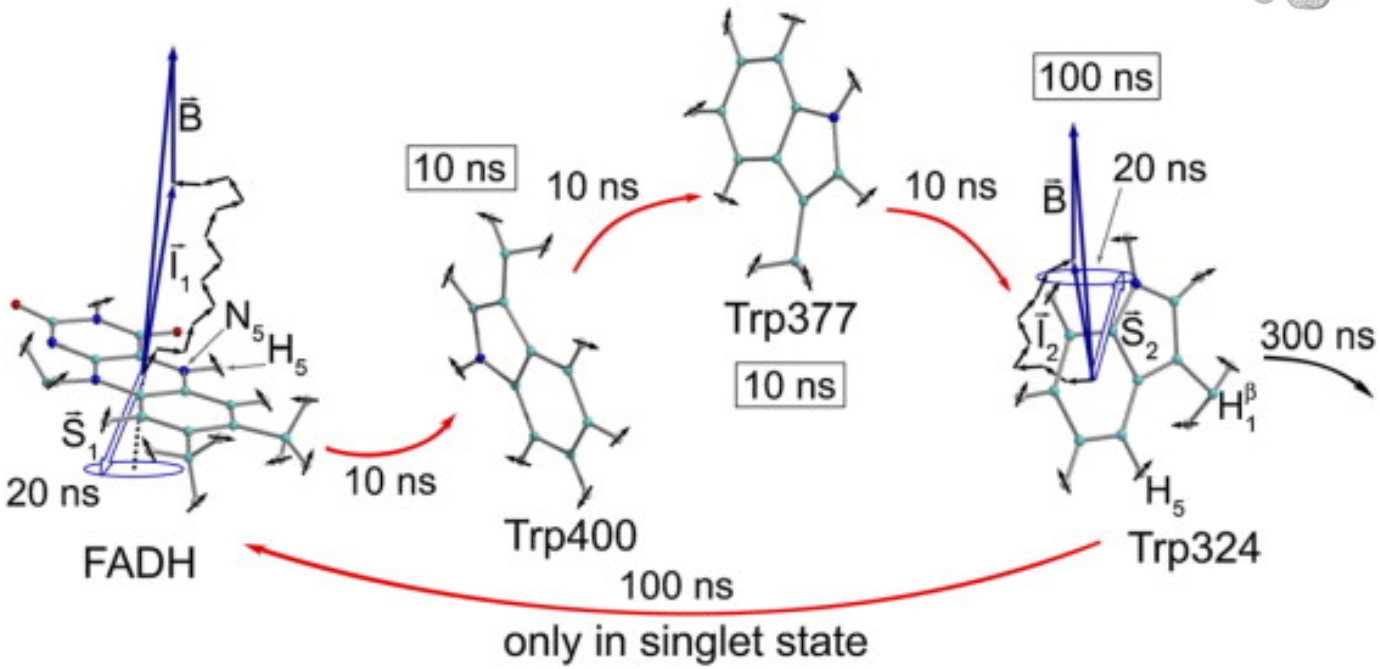
University of Illinois at Urbana-Champaign

Excitation and Electron Transfer



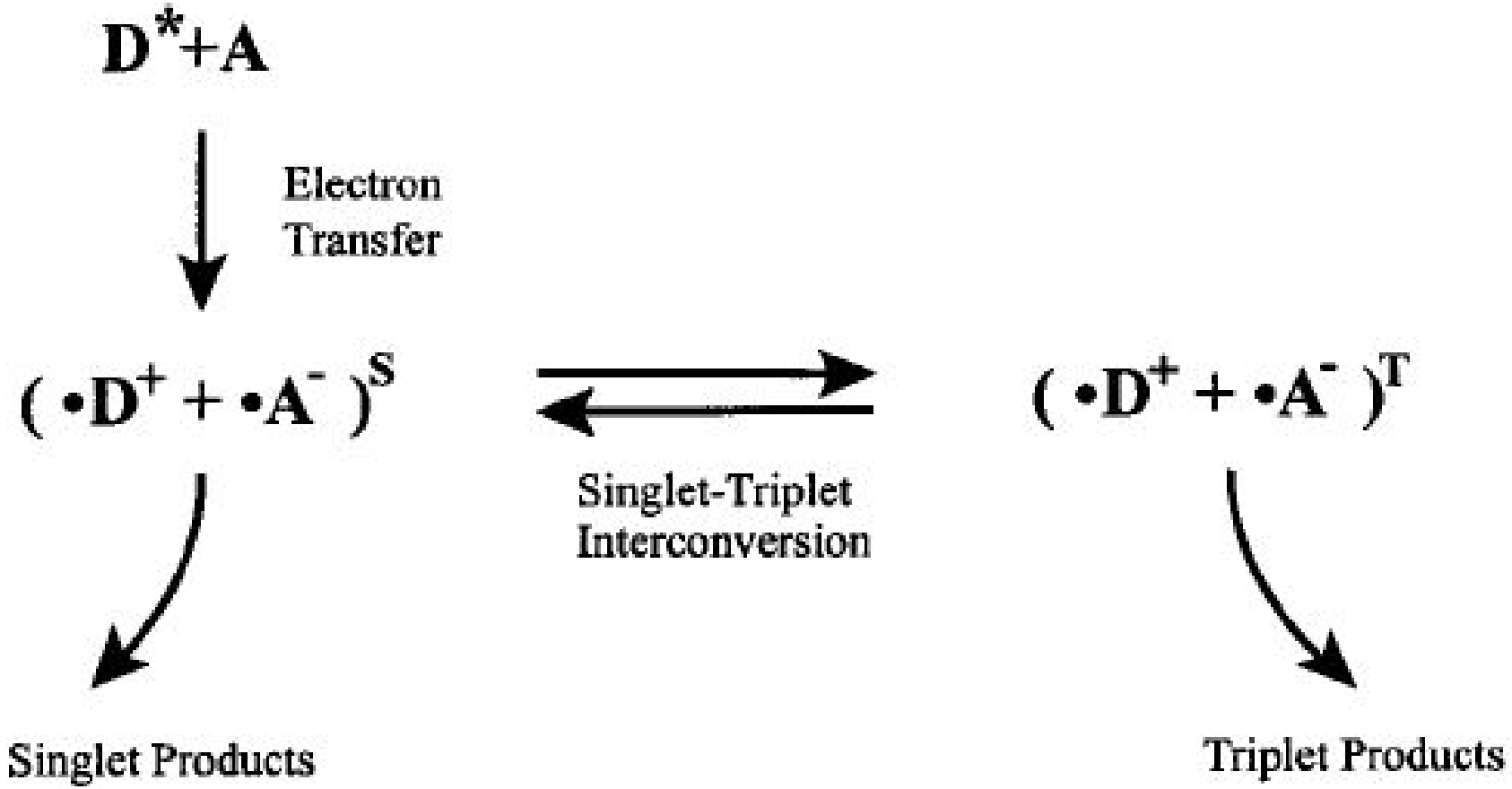


6.0 Angstroms ⟷

8.9 Angstroms ⟷

13.3 Angstroms ⟷

Theory


D*+A
Electron Transfer
(•D+ + •A-)S
(•D+ + •A-)T
Singlet-Triplet Interconversion
Singlet Products
Triplet Products

Rationale for a Radical Pair Mechanism

- Orientation of birds is effected by certain wavelengths and intensities of light.
- Radio frequency interference.
- Cryptochrome is a common documented photo receptor protein.
- Demonstrated role in magnetic orientation of fruit flies.
- Narrow range of field strength.

The Hamiltonian of the system is

$$\mathrm{H}=\mathrm{g}\mu_B \cdot \sum_{j=1}^{2} \overrightarrow{S_j} \cdot (\vec{B} + \overleftrightarrow{A_j} \cdot \overrightarrow{I_j})$$

The density matrix of the system is governed by the stochastic Liouville Equation:

$$\dot{\rho}(t) = -\frac{i}{\hbar}[H, \rho(t)] - \frac{k_S}{2}\{Q^S, \rho(t)\} - \frac{k_T}{2}\{Q^T, \rho(t)\}$$

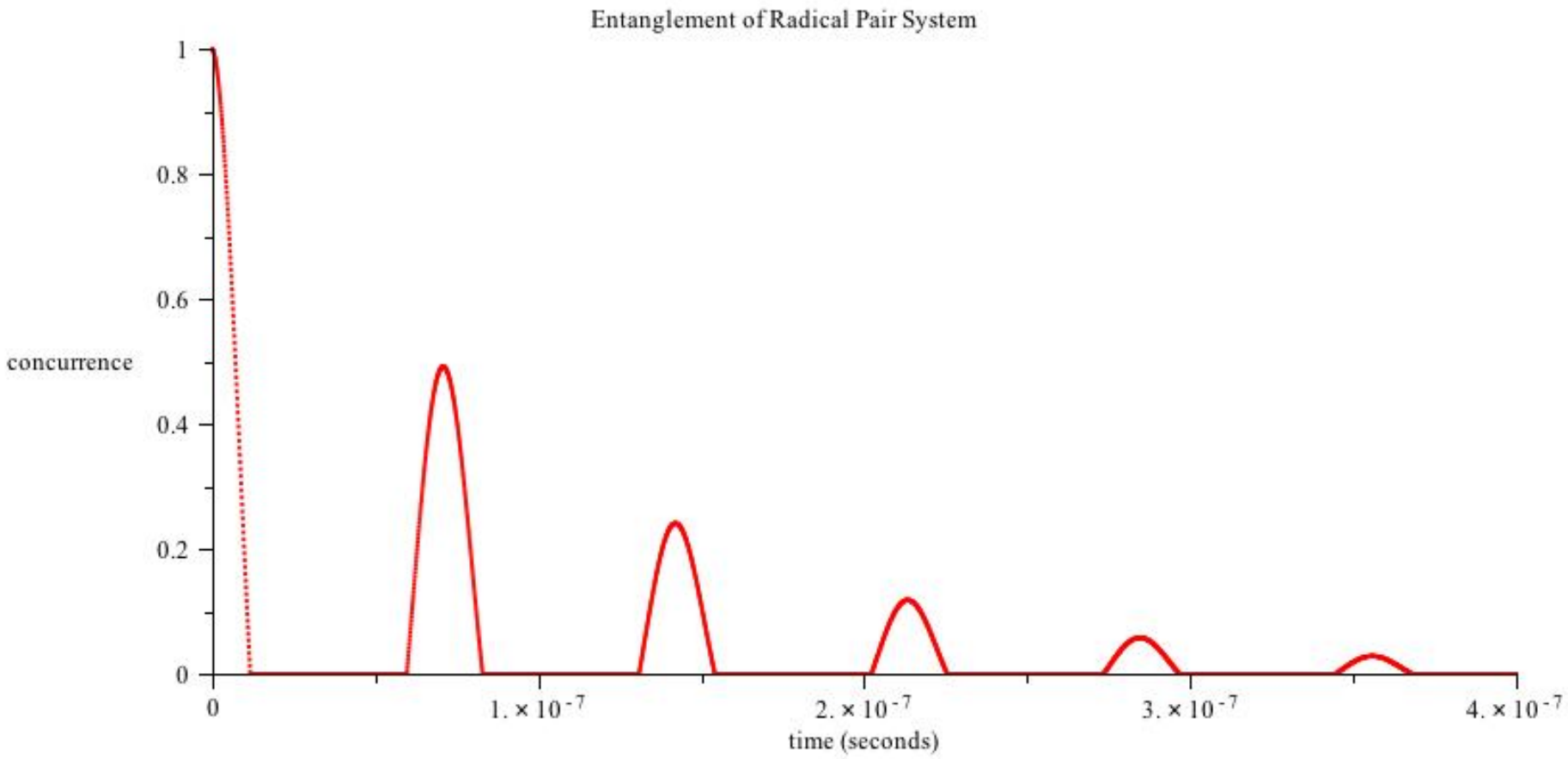
Calculating Entanglement

Concurrence

$$C = \max\{0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\}$$

$$R = \rho(\sigma_y \otimes \sigma_y \rho^* \sigma_y \otimes \sigma_y)$$

Concurrence



Bell Inequality

Bell inequality:

$$E = E(0,0) + E(0,t) + E(t,0) - E(t,t)$$

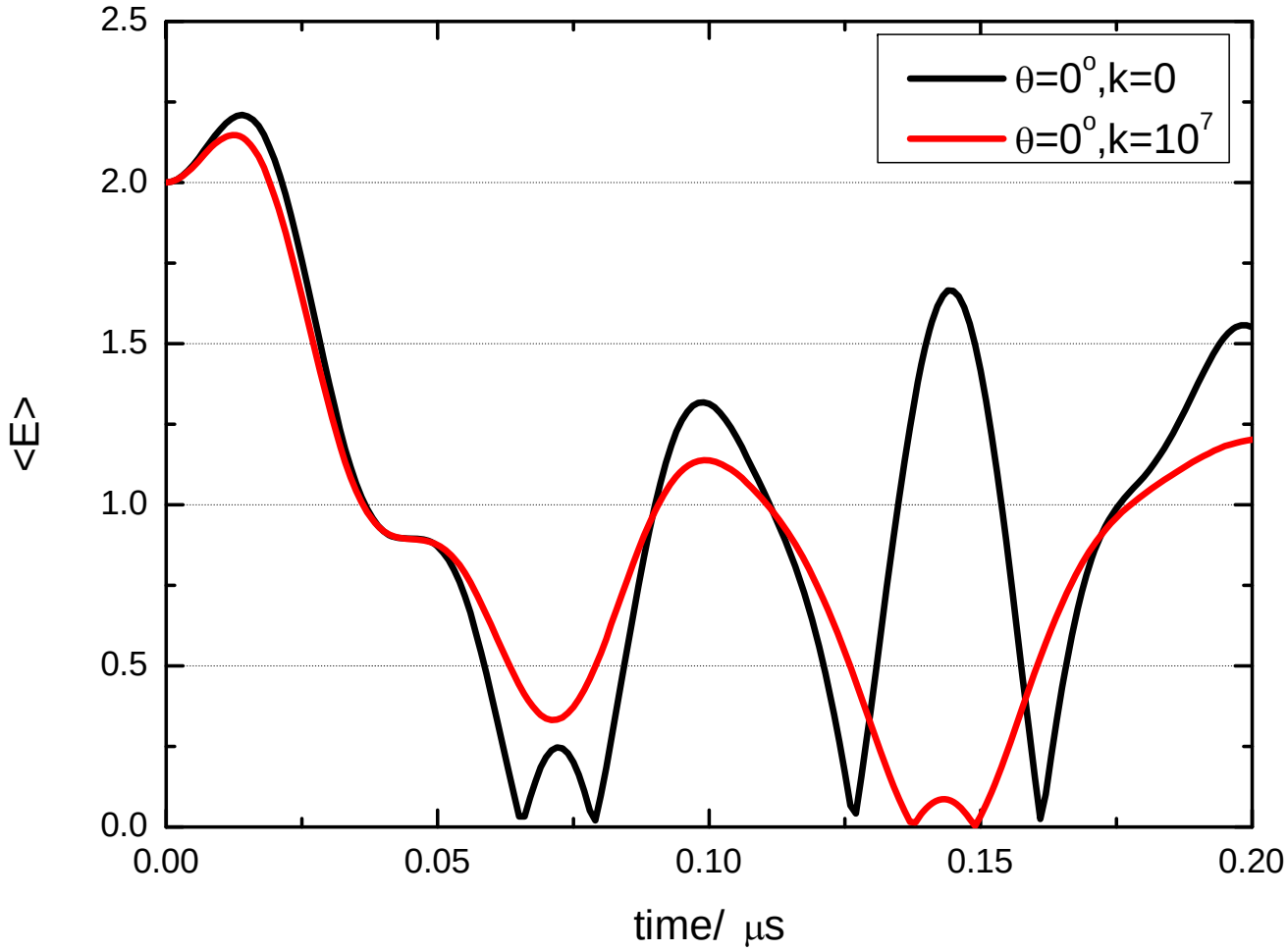
Where

$$E(t_1, t_2) = \left\langle \varphi_{t_1} \left| (\vec{\sigma}_{t_1} \cdot \vec{a})(\vec{\sigma}_{t_2} \cdot \vec{b}) \right| \varphi_{t_2} \right\rangle$$

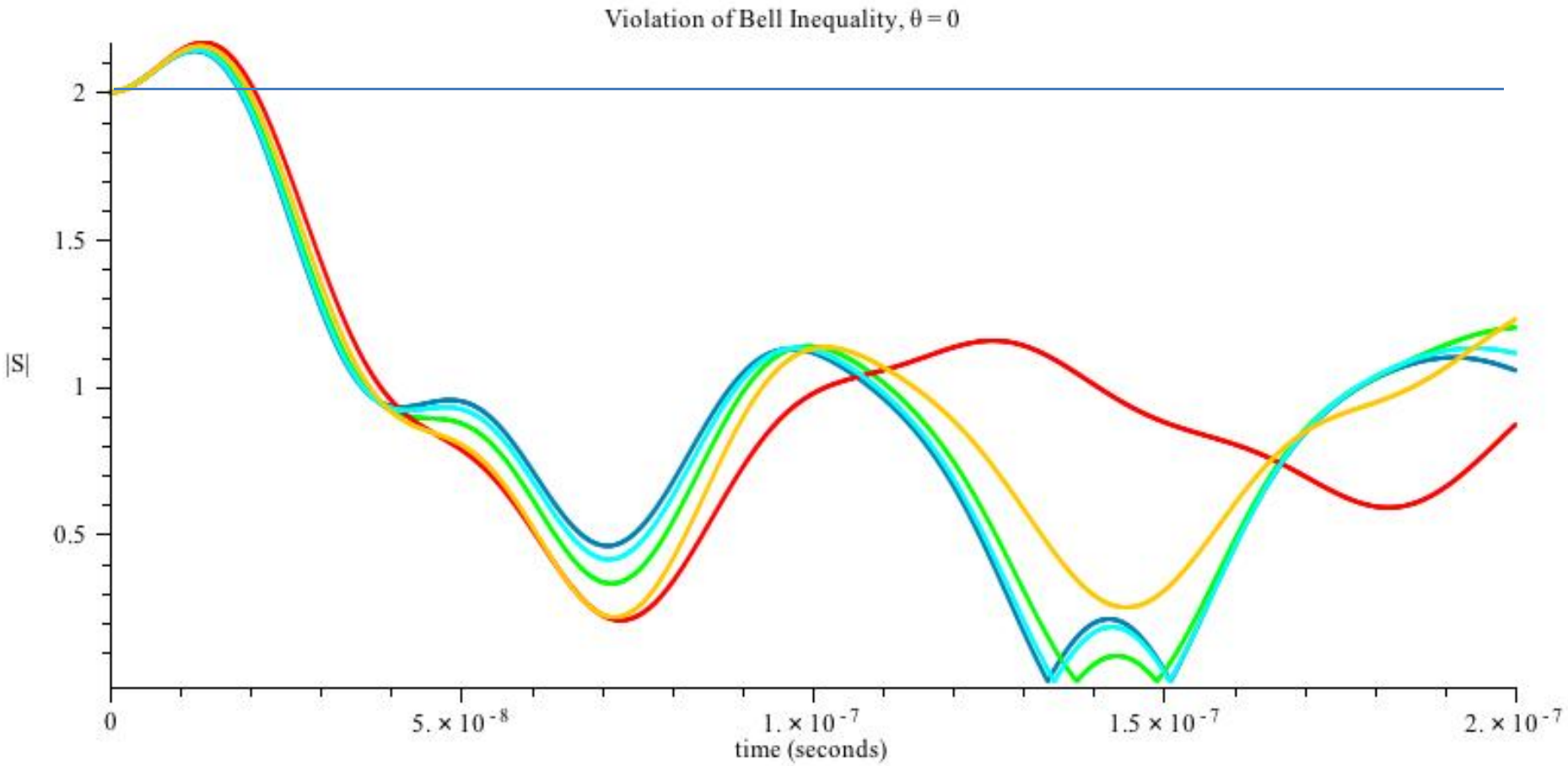
System is entangled for

$$E > 2\lambda^2 = 2$$

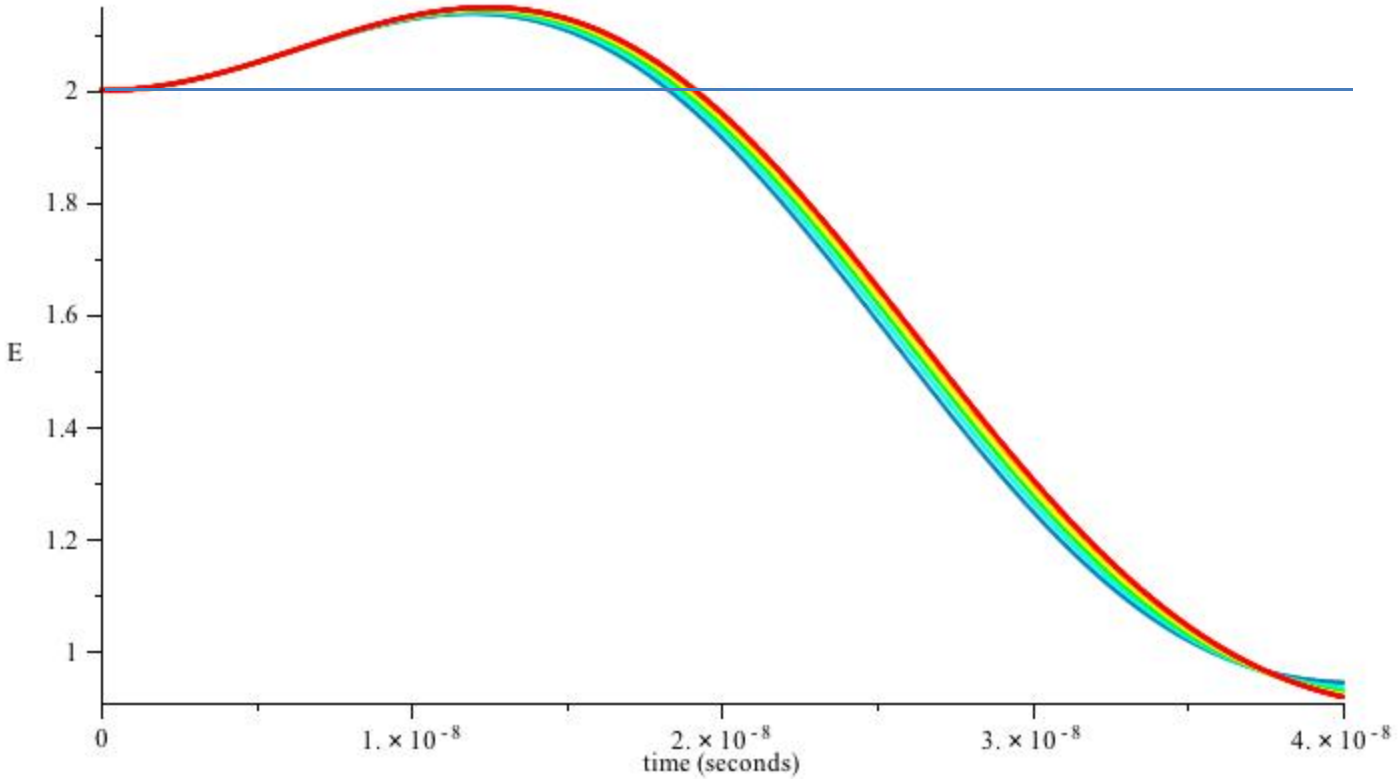
Bell Inequality



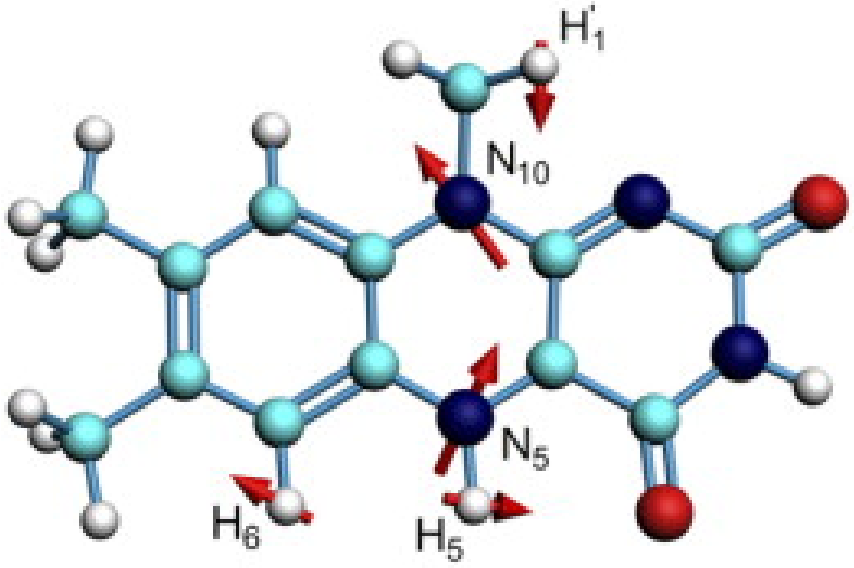
Violation of Bell Inequality



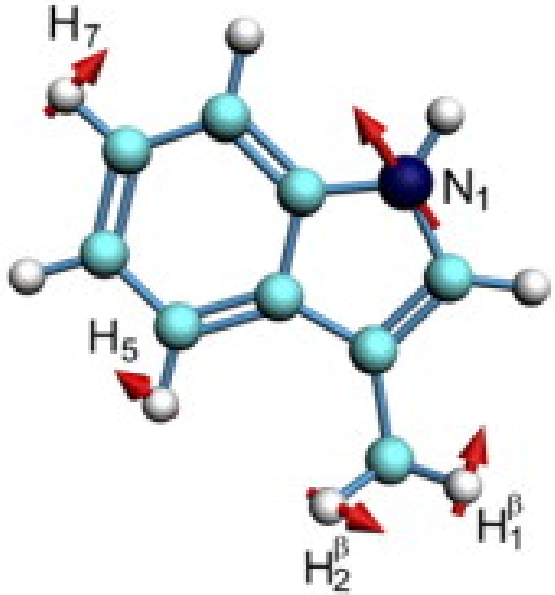
Violation of Bell Inequality



Magnetic Fields from Ring Currents



FADH



Tryptophan

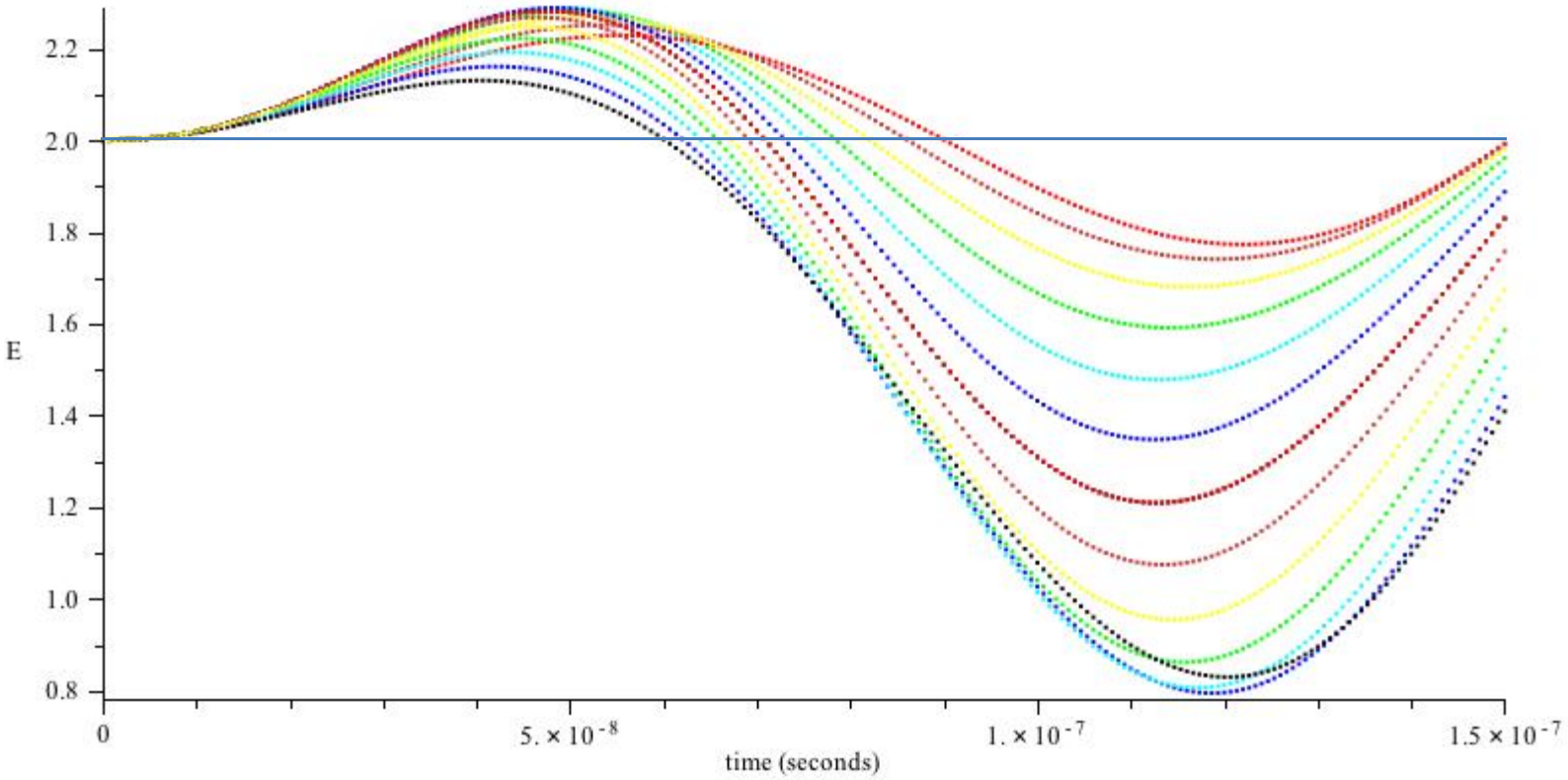
Hamiltonian

$$H = H_1 + H_2$$

$$H_i = g\mu_B \vec{S}_i \cdot (\vec{B}_i + \vec{B}_{Earth})$$

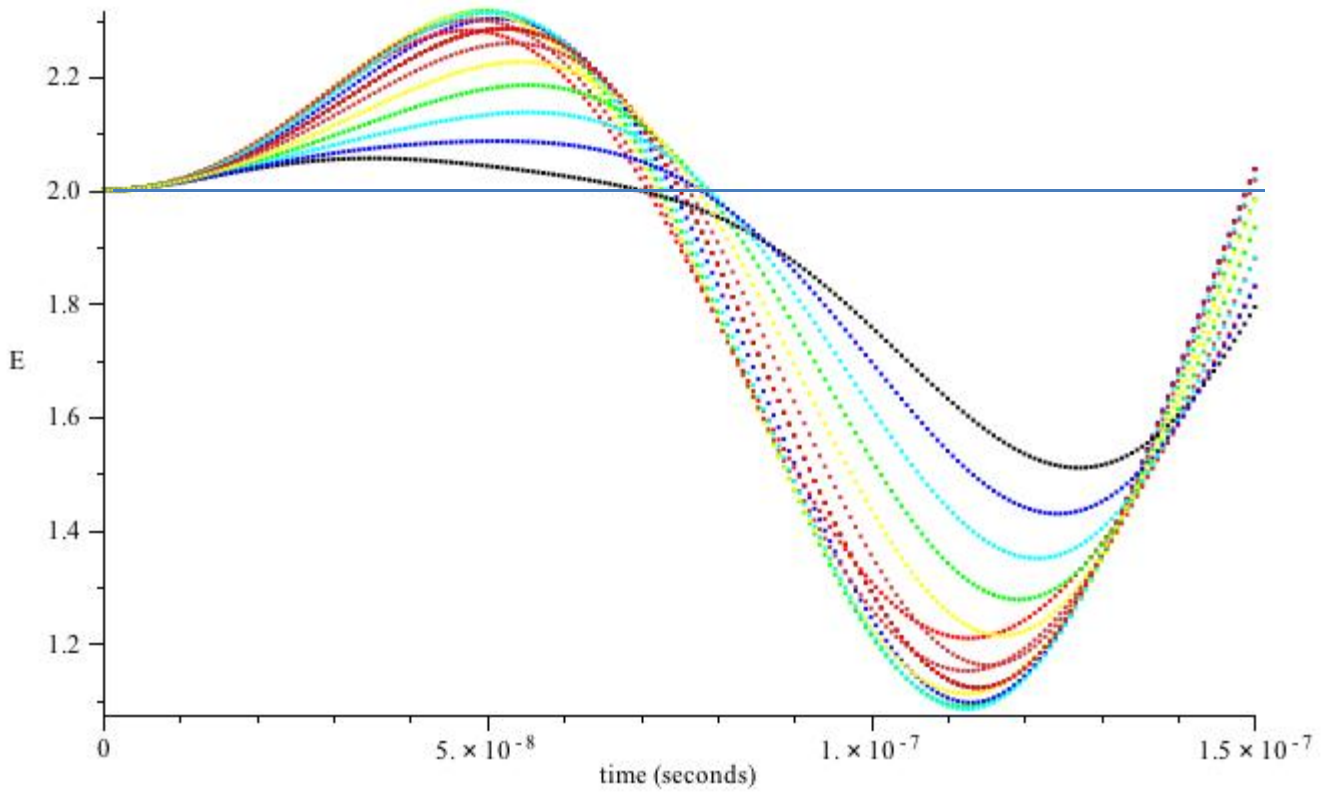
$$\vec{B}_1 = \begin{bmatrix} 0 \\ 0 \\ 4G \end{bmatrix} \quad \vec{B}_2 = \begin{bmatrix} 0 \\ 5G \\ 0 \end{bmatrix}$$

Dependence on θ



$\phi = 0$

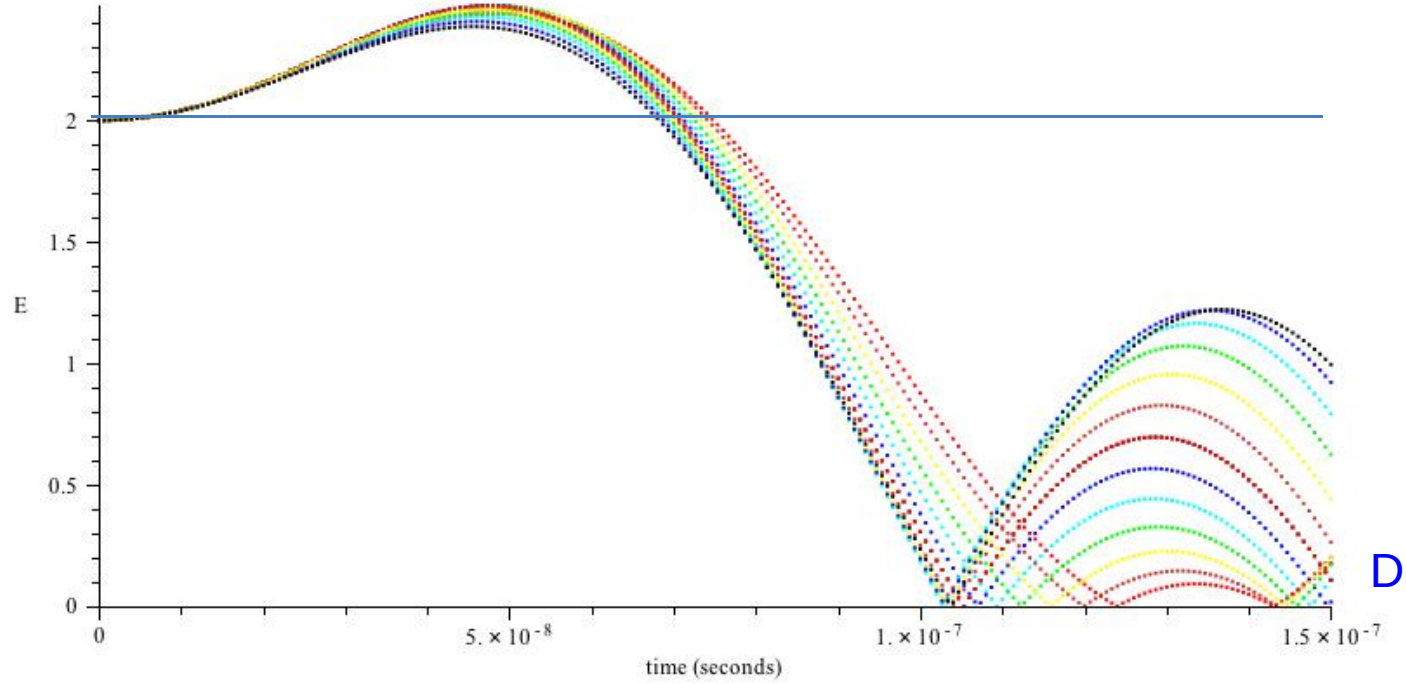
Dependence on ϕ



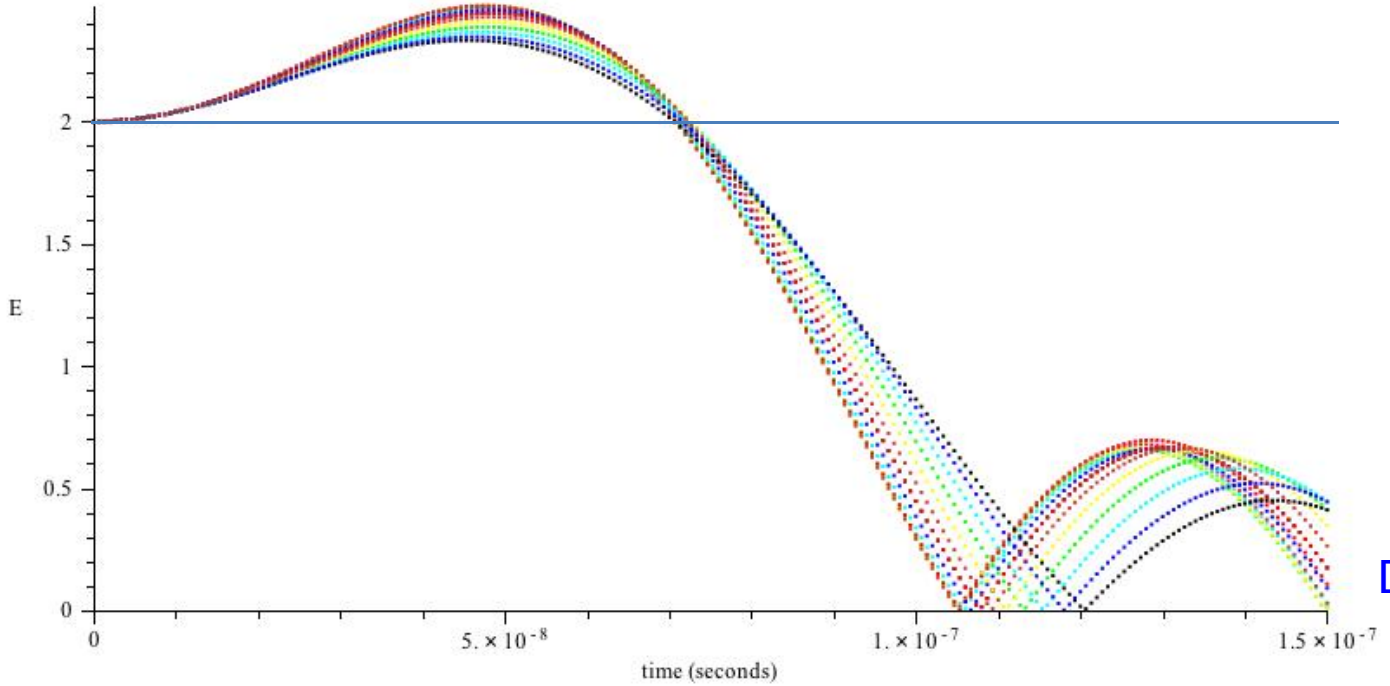
$\theta = 90$

$$\vec{B}_1 = \begin{bmatrix} 0 \\ 0 \\ 2G \end{bmatrix}$$

$$\vec{B}_2 = \begin{bmatrix} 0 \\ 5G \\ 0 \end{bmatrix}$$



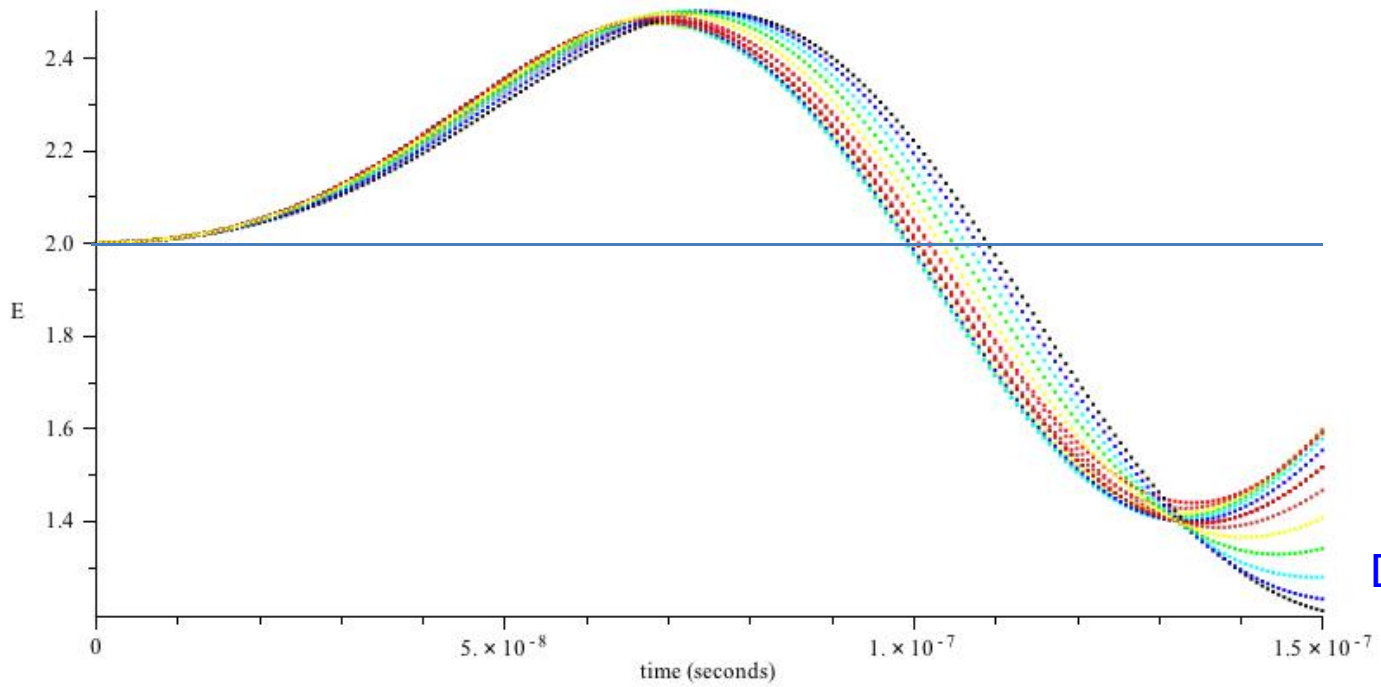
Dependence on θ



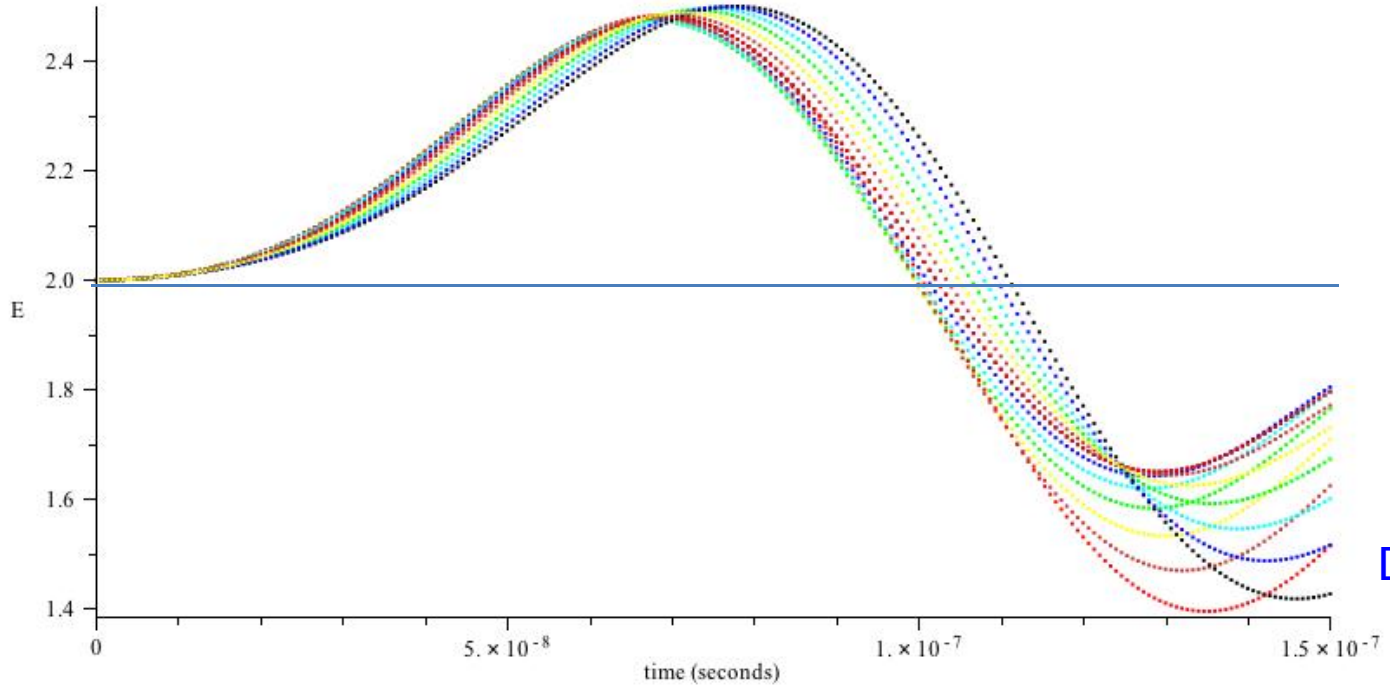
Dependence on ϕ

$$\vec{B}_1 = \begin{bmatrix} 0 \\ 2G \\ 2G \end{bmatrix}$$

$$\vec{B}_2 = \begin{bmatrix} 0 \\ 5G \\ 0 \end{bmatrix}$$



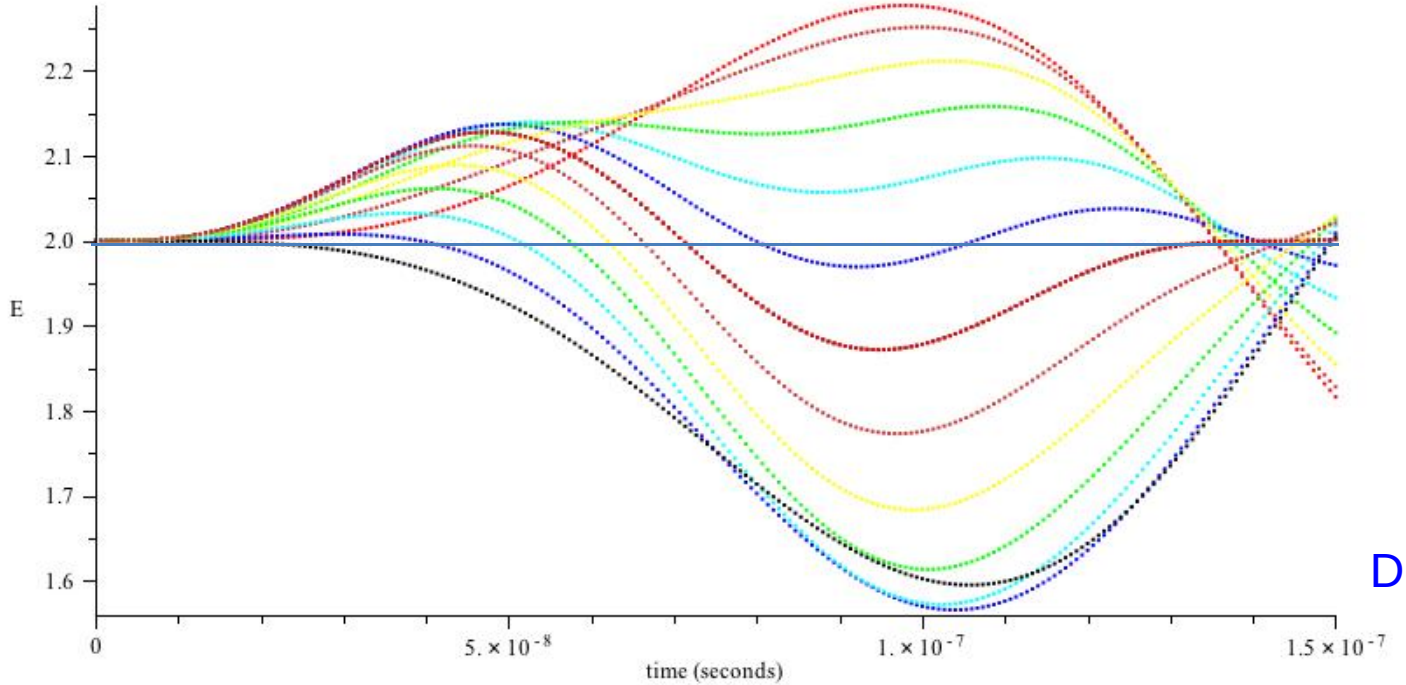
Dependence on θ



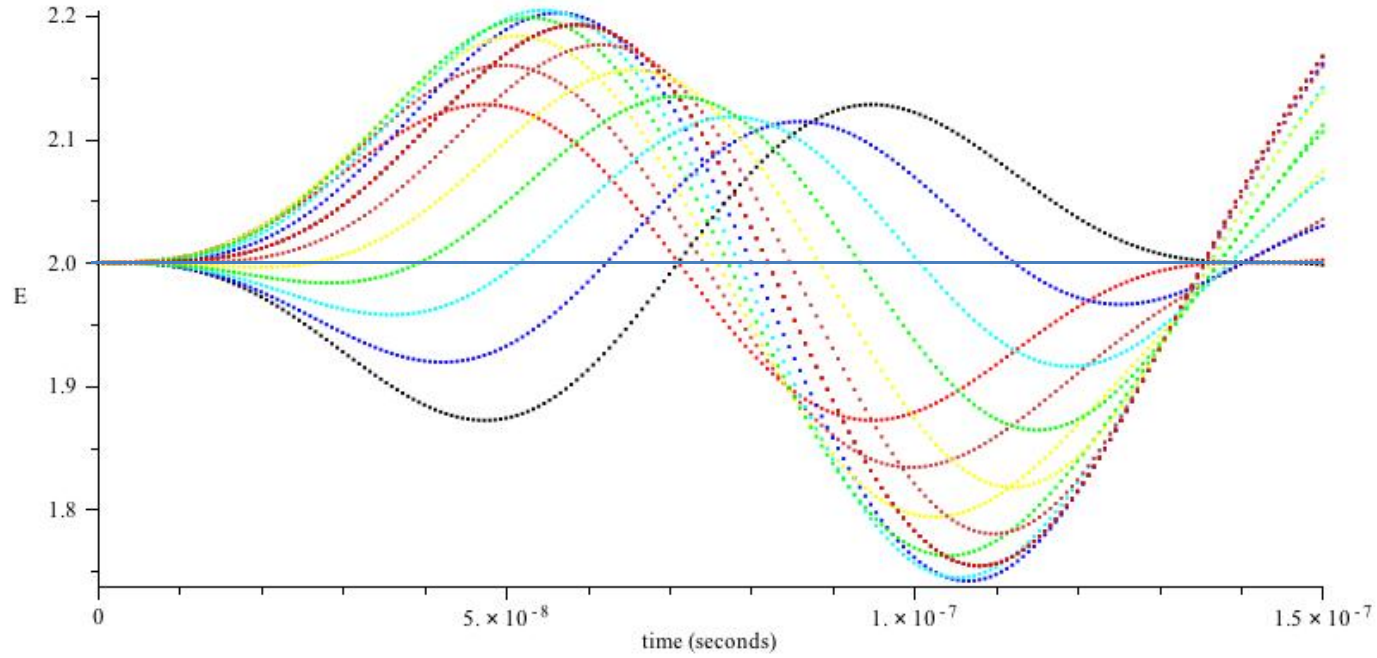
Dependence on ϕ

$$\vec{B}_1 = \begin{bmatrix} 0 \\ 0 \\ 5G \end{bmatrix}$$

$$\vec{B}_2 = \begin{bmatrix} 0 \\ 5G \\ 0 \end{bmatrix}$$



Dependence on θ



Dependence on ϕ

Conclusions

- Entanglement is not involved in the nuclear spin model.
- Perpendicular local fields do produce a model in which entanglement could play a role.
- Orientation is a very important factor.

Acknowledgements

- Purdue University
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