Application of Quantum Mechanics to Biology

- How can we apply quantum mechanics to biology?
- Polymers of nucleotides and amino acids - millions of atoms bounded into a large molecule
Visual System

- Must turn light into electrical signal for neurons to process
- Visual pigments in the eyes can absorb light and transduce an electric signal
- Rhodopsin is the pigment responsible
- Rhodopsin is covalently attached to opsin (protein)
- Rhodopsin is 11-cis-retinal, which can be converted to 11-trans-retinal at the appropriate wavelength of light.
- Photoexcitation causes the activation of phosphodiesterase - hydrolyze 3’-5’cyclic GMP
- Close sodium channels
Quantum Mechanics in the Visual System

- Two types of cells that sense light - Rod and Cone cells
- Rod cells - absorb 500nm
- Cone cells - absorb 580nm
- Both cells utilize Rhodopsin as a pigment
- Rhodopsin absorbs at 380nm
- Rhodopsin is attached to a protein called opsin through a lysine
- Attached form of Rhodopsin absorbs 450nm. Why?
Quantum Mechanics in the Visual System

• trans rhodopsin has 145kJ/mol more energy than cis rhodopsin

• in solution it is just a few kJ/mol. Why??

• Energy of visible light.

  • \( E = h\nu = \frac{hc}{\lambda} \)  
    \( h = \text{Plank’s constant} = 6.626 \times 10^{-34} \text{ Js} \)  
    \( c = 3.0 \times 10^8 \text{ m/s} \)
Light Driven Isomerization of Rhodopsin
Fluorescence

- Fluorescence is a type of light emitted going from the excited electronic state back to the ground state.
Fluorescence in Biology

- Many biological substances emit fluorescence
- Green fluorescent protein
- tryptophan in proteins
- flavoproteins
- reduced pyridine nucleotides
- Bioluminescence produces light without absorption
Fluorescence Theory

- Excitation results in the molecule going into a higher vibrational and electronic state.
- The excited molecule will lose some (but not all) of its excited energy.
  - This energy loss results in the release of heat - nonradiative (no EM released). This is called internal conversion.
- Once in the ground excited state, the molecule will release light - fluorescence.
- The emitted light will be of lower frequency and energy.
Absorption and Fluorescence

Absorption and fluorescence of bacteriochlorophyll. (a) Energy-level diagram showing spectral transitions (vertical arrows). The energy levels are broadened (shading) by vibrational sublevels that are not usually resolved in solution spectra. (b) Absorption spectrum corresponding to energy levels of part (a). This spectrum is turned 90° from the usual orientation to show the relation to the energy levels. (c) Radiationless relaxation (dashed arrows) and fluorescence (shaded arrow). (d) Fluorescence emission spectrum corresponding to part (c). Note the red shift of the fluorescence compared with the corresponding Q absorption illustrated in parts (a) and (b). [From K. Sauer, 1975, in Bioenergetics of Photosynthesis, ed. Govindjee (New York: Academic Press), 115–181.]
Properties of Fluorescence

• The absorption and fluorescence spectra will often resemble each other since similar excited states are involved.

• Like absorption, fluorescence is sensitive to environment.

• The lifetime of the excited state is an indication of environment
Excited-state Properties

- sample absorbs EM to produce the excited state, fluoresces, and then decays.
- decay is usually first order and exponential (will discuss kinetics later)
- two important terms:
  - fluorescence decay time or lifetime ($\tau$)
  - quantum yield $\phi$ where $\phi=\text{# fluorescent photons/ # of photons absorbed}$
Lifetimes and Quantum Yields

- Lifetimes ($\tau$) and quantum yields ($\phi$) are important properties of fluorescent molecules.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Medium</th>
<th>$\tau$, ns</th>
<th>$\phi$</th>
<th>Reference$^*$</th>
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<tbody>
<tr>
<td>fluorescein</td>
<td>0.1 M NaOH</td>
<td>4.62</td>
<td>0.93</td>
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<td>Quinine sulfate</td>
<td>0.5 M H$_2$SO$_4$</td>
<td>19.4</td>
<td>0.54</td>
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<tr>
<td>9-Aminoaacidine</td>
<td>Ethanol</td>
<td>15.15</td>
<td>0.99</td>
<td>a</td>
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<tr>
<td>Phenylalanine</td>
<td>H$_2$O</td>
<td>6.4</td>
<td>0.004</td>
<td>b</td>
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<tr>
<td>Tyrosine</td>
<td>H$_2$O</td>
<td>3.2</td>
<td>0.14</td>
<td>b</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>H$_2$O</td>
<td>3.0</td>
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<tr>
<td>Cytidine</td>
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<td>0.03</td>
<td>c</td>
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<tr>
<td>Adenyl acid (AMP)</td>
<td>H$_2$O, pH 1</td>
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<td>0.004</td>
<td>c</td>
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<tr>
<td>Etheno-AMP</td>
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<td>Diethyl ether</td>
<td>5.0</td>
<td>0.32</td>
<td>e</td>
</tr>
<tr>
<td>Chlorophyll $b$</td>
<td>Diethyl ether</td>
<td>—</td>
<td>0.12</td>
<td>e</td>
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<tr>
<td>Chloroplasts</td>
<td>H$_2$O</td>
<td>0.35–1.9</td>
<td>0.03–0.08</td>
<td>f</td>
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<tr>
<td>Riboflavin</td>
<td>H$_2$O, pH 7</td>
<td>4.2</td>
<td>0.26</td>
<td>g</td>
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<tr>
<td>DANSYL sulfonamide$^+$</td>
<td>H$_2$O</td>
<td>3.9</td>
<td>0.55</td>
<td>h</td>
</tr>
<tr>
<td>DANSYL sulfonamide + carbonic anhydrase</td>
<td>H$_2$O</td>
<td>22.1</td>
<td>0.84</td>
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<tr>
<td>DANSYL sulfonamide + bovine serum albumin</td>
<td>H$_2$O</td>
<td>22.0</td>
<td>0.64</td>
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</tbody>
</table>
Fluorescence Quenching

- Fluorescence can be quenched by colliding with specific quenching molecules, transfer of energy to nonfluorescent materials, complex formation or aggregation into a nonfluorescent form, or self-absorption of fluorescence energy.

- In order to transfer fluorescence requires collisions so the molecules need to be in close proximity.

- Dissolved O$_2$ can quench fluorescence.

- Benzene O$_2$ free solution $\tau=29$ns, while with O$_2$ at 1atm $\tau=5.7$ns.

- Longer the lifetime, the increased probability of quenching.

- Changing of fluorescence intensity due to the changes in environment is often used in biological systems to study their function.

- We are fluorescent and the change of fluorescent intensity can provide information about the environment of the W.
Excitation Transfer

- Excitation transfer from one molecule to another
- The transfer strongly depends on both distance and orientation of the donor and acceptor
- Transfer can be measured in three ways
  - Decrease in fluorescence intensity due to the presence of donor
  - Decrease in the lifetime of the fluorescence
  - The acceptor absorbs the fluorescence of the donor and acceptor fluoresces
Fluorescence Resonance Energy Transfer (FRET)

• The transfer of energy from donor to acceptor

• The efficiency transfer is determined by lifetimes \( \text{Eff} = 1 - \left( \frac{\tau_{D+A}}{\tau_D} \right) \)

• The transfer is directly related to the distance (1-10nm)

• \( \text{Eff} = \frac{r_0^6}{(r_0^6 + r^6)} \) where \( r \) is the distance between donor and acceptor and \( r_0 \) is the distance where \( \text{Eff} = 0.5 \)
Molecular Rulers

- Transfer of energy can occur over distances several times the size of the molecule.
- FRET can be used to determine distance between donor and acceptors.
- This is useful for determining whether two molecules are in close proximity within a cell.

![Graph showing efficiency of energy transfer as a function of distance](image)