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 a the activation of phosphodiesterase - hydrolyze 3’-5’cyclic GMP
- close sodium channels

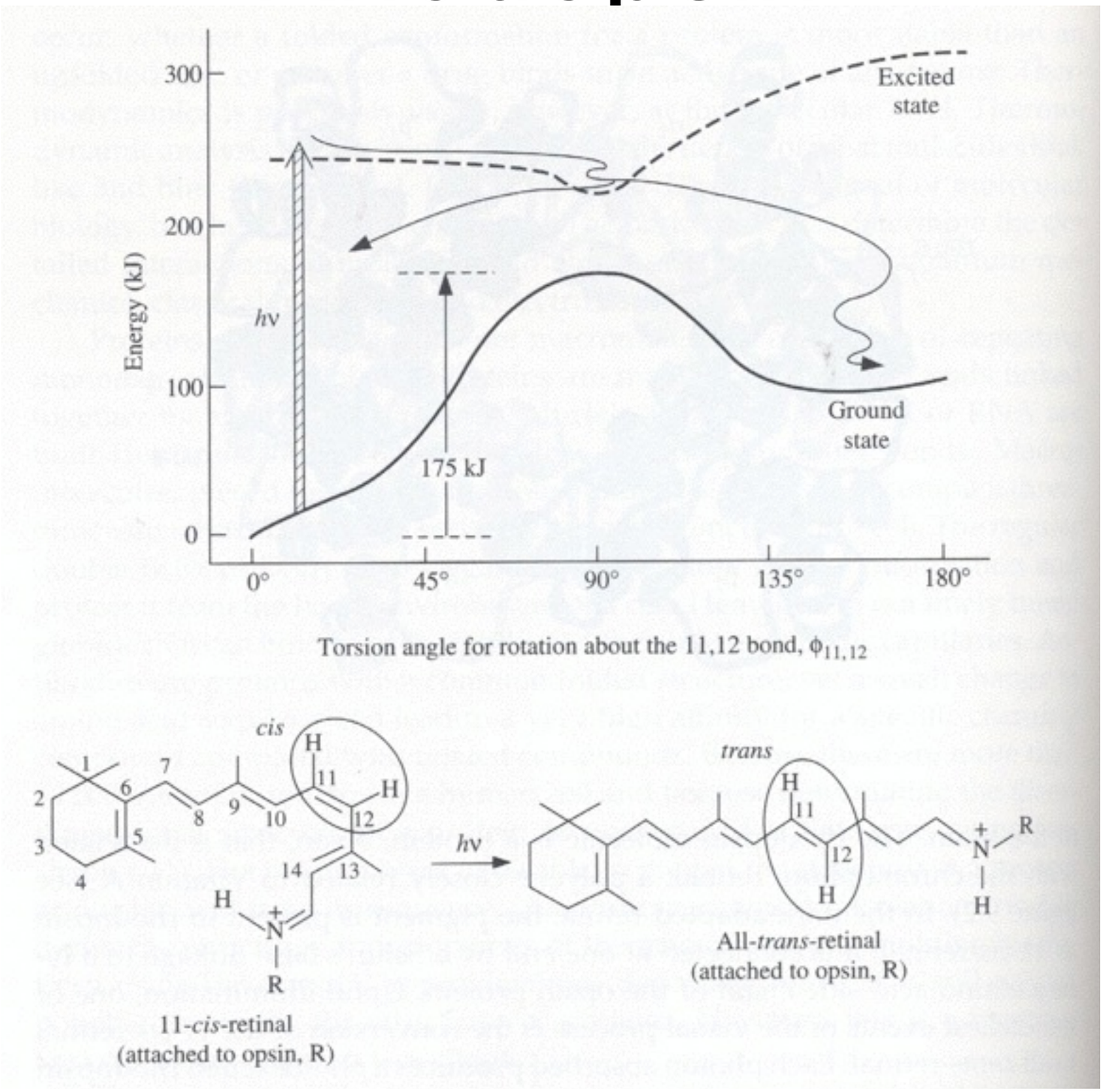
Quantum Mechanics in the Visual System

- 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

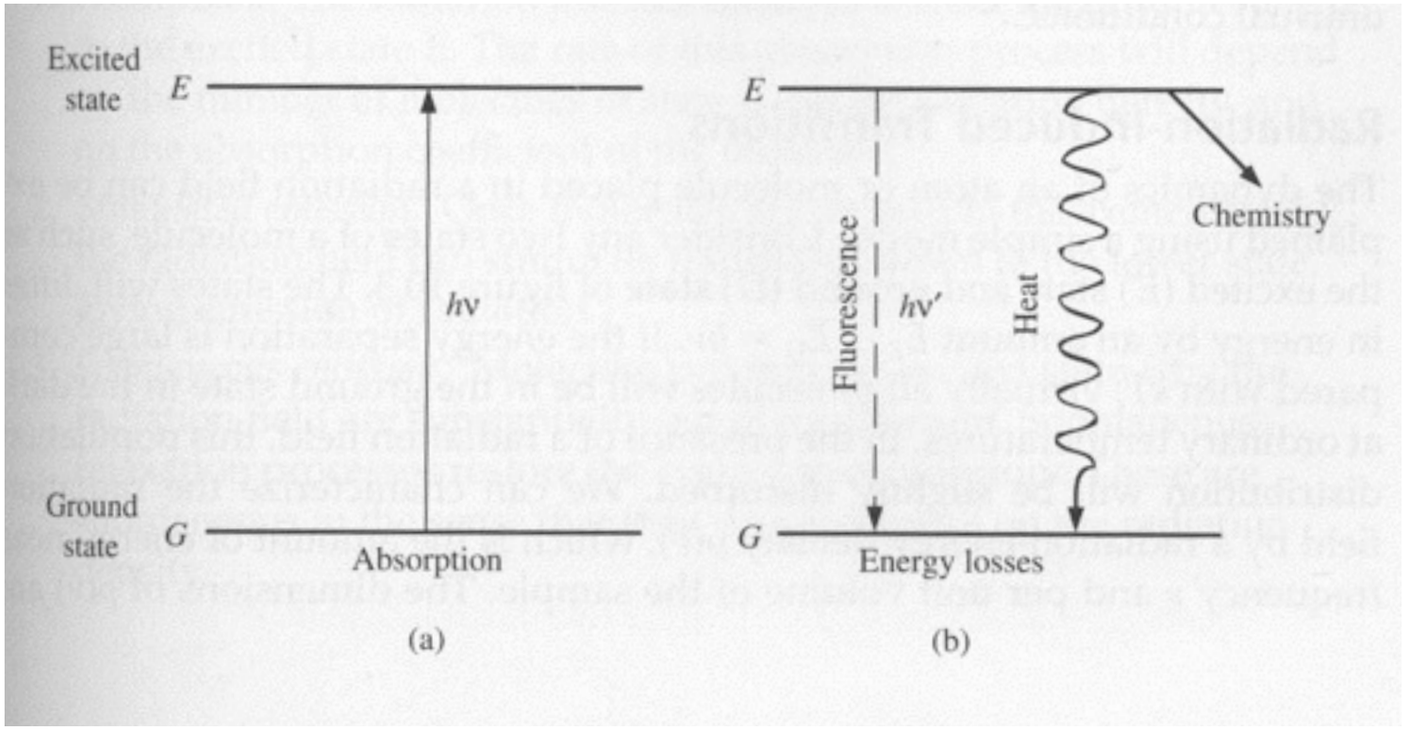
- trans rhodopsin has 145kJ/mol more energy than cis rhodopsin
- in solution it is just a few kJ/mol. Why??
- Energy of visible light.
  - $E=hv= hc/\lambda$ h=Plank's constant=$6.626x10^{-34}$ Js c=$3.0x10^{8}$ m/s

Light Driven Isomerization of Rhodopsin



Fluorescence

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



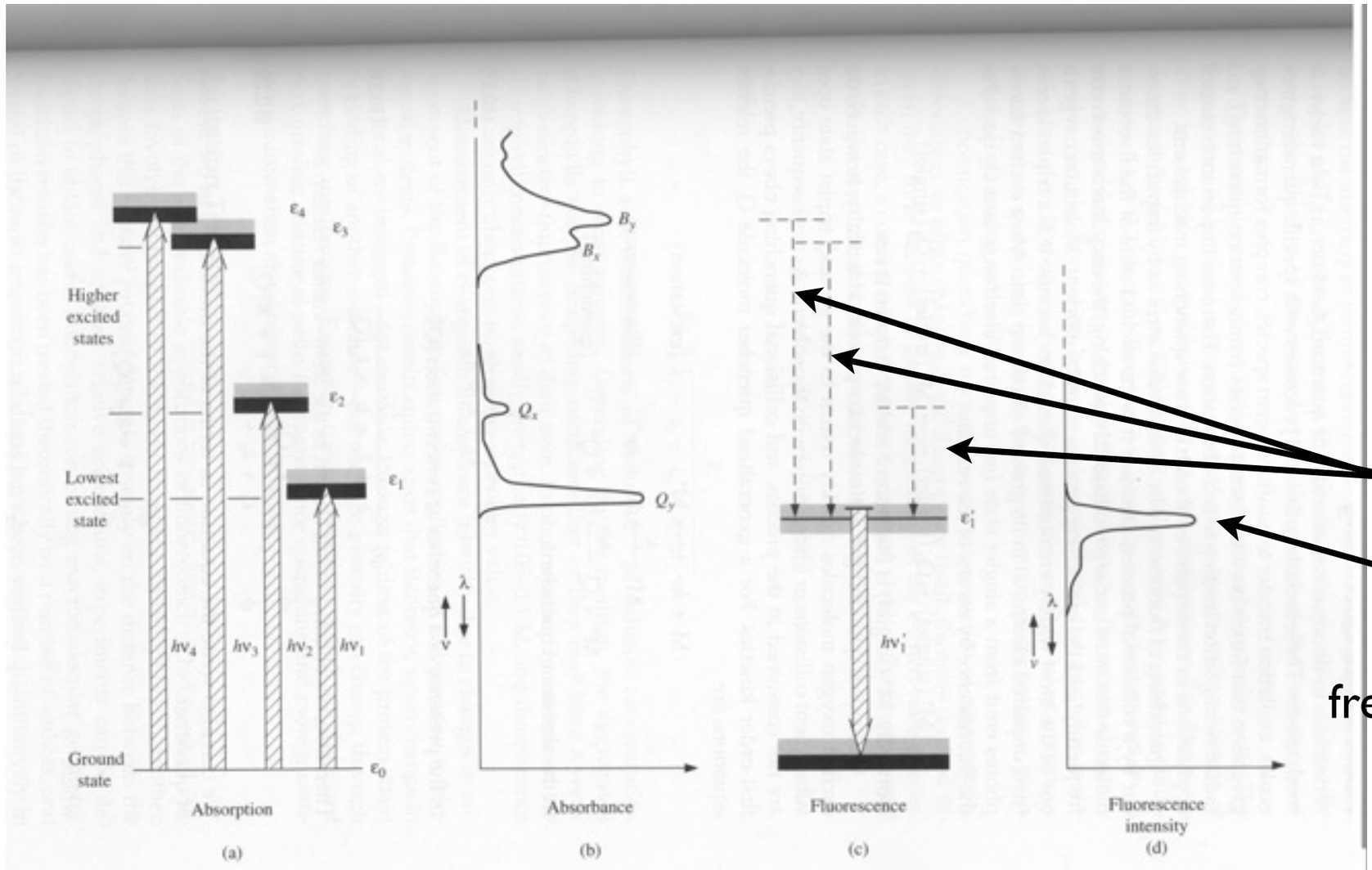
Fluorescence in Biology

- 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



▲ FIGURE 10.17

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_y absorption illustrated in parts (a) and (b). [From K. Sauer, 1975, in *Bioenergetics of Photosynthesis*, ed. Govindjee (New York: Academic Press), 115–181.]

Heat released

Fluorescence
EM emitted at a lower frequency relative to input

Properties of Fluorescence

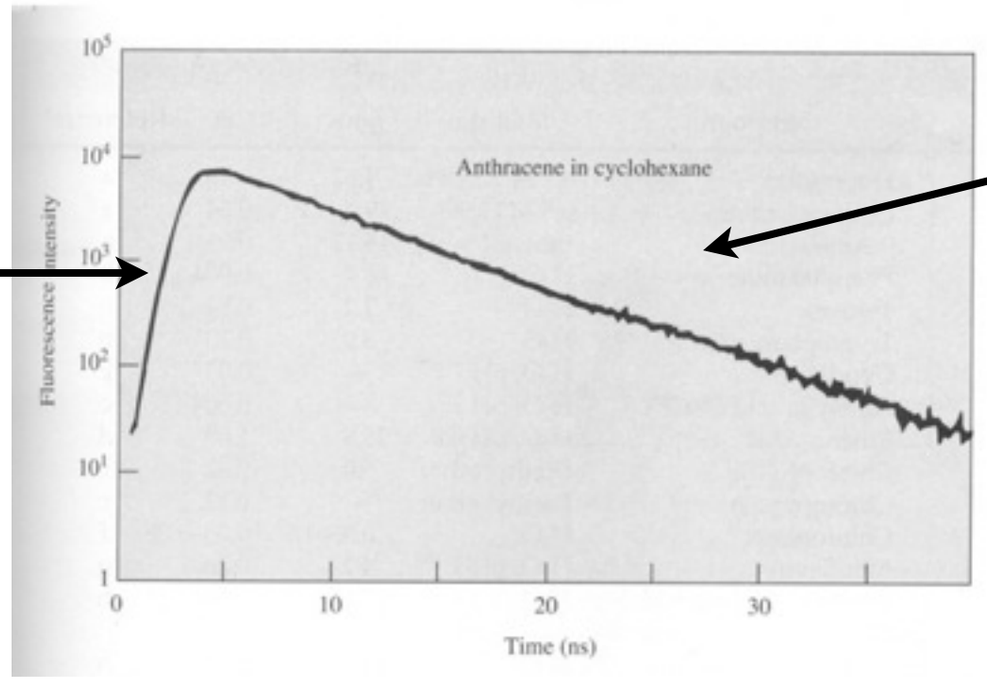
- The absorption and fluorescence spectra will often resemble each other since similar excited states are involved.
- Like absorption, fluorescence is sensitive to environment.
- The lifetime of the excited state is an indication of environment

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 (τ)
    - quantum yield ϕ where ϕ=# fluorescent photons/ # of photons absorbed

absorption

fluorescence



◀ FIGURE 10.16
Fluorescence decay of anthracene in cyclohexane (1.7×10^{-3} *M*), excited by a light flash of 1.4-ns duration (half width) and at approximately 360 nm. Emission measured at 450 nm. Logarithmic decay curve, obtained using single-photon counting method. (From P. R. Hartig, K. Sauer, C. C. Lo, and B. Leskovar, 1976, *Rev. Sci. Instrum.* 47:1122.)

Lifetimes and Quantum Yields

- Lifetimes (τ) and quantum yields (ϕ) are important properties of fluorescent molecules

TABLE 10.5 Fluorescence Quantum Yields and Radiative Lifetimes

Compound	Medium	τ, ns	ϕ	Reference*
Fluorescein	0.1 *M* NaOH	4.62	0.93	a
Quinine sulfate	0.5 *M* H_2SO_4	19.4	0.54	a
9-Aminoacridine	Ethanol	15.15	0.99	a
Phenylalanine	H_2O	6.4	0.004	b
Tyrosine	H_2O	3.2	0.14	b
Tryptophan	H_2O	3.0	0.13	b
Cytidine	H_2O, pH 7	—	0.03	c
Adenylic acid (AMP)	H_2O, pH 1	—	0.004	c
Etheno-AMP	H_2O, pH 6.8	23.8	1.00	d
Chlorophyll *a*	Diethyl ether	5.0	0.32	e
Chlorophyll *b*	Diethyl ether	—	0.12	e
Chloroplasts	H_2O	0.35–1.9	0.03–0.08	f
Riboflavin	H_2O, pH 7	4.2	0.26	g
DANSYL sulfonamide†	H_2O	3.9	0.55	h
DANSYL sulfonamide + carbonic anhydrase	H_2O	22.1	0.84	h
DANSYL sulfonamide + bovine serum albumin	H_2O	22.0	0.64	h

Fluorescence Quenching

- Fluorescence can be quench 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 τ=29ns, while with O_2 at 1atm τ=5.7ns
- 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.
    - W are fluorescent and the of the fluorescent intensity can provide information about the of the environment of the W

Excitation Transfer

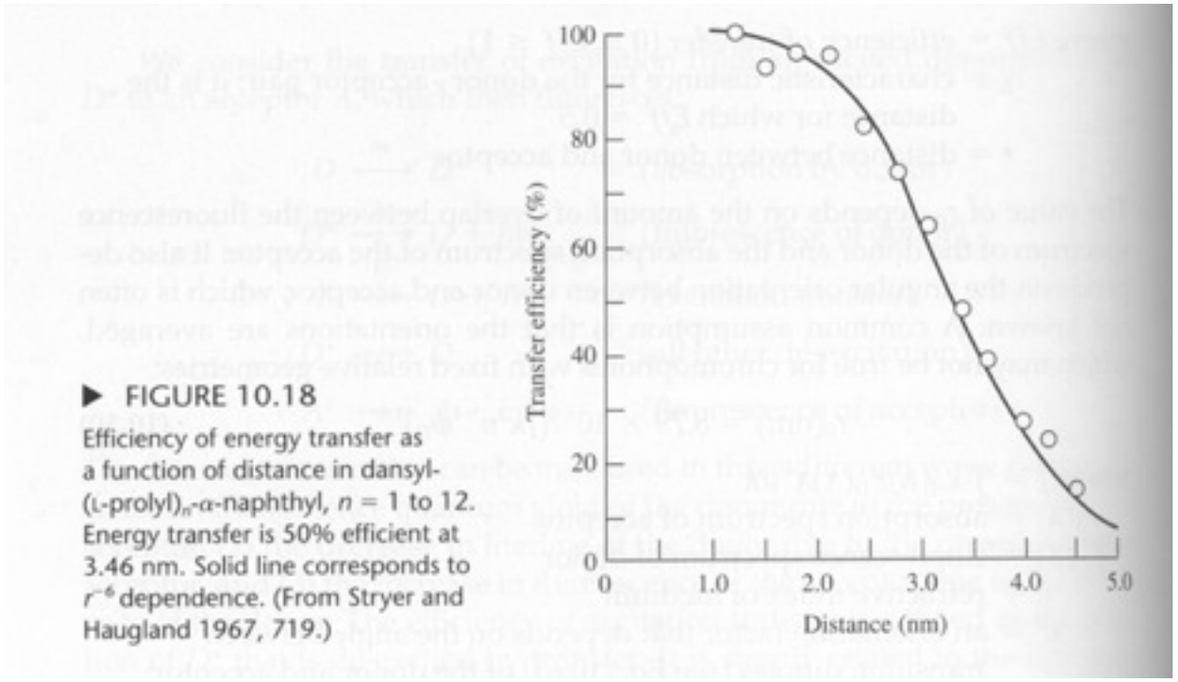
- Excitation transfer from one molecule to another
- The transfer strongly depends on both distance and orientation of the donor and acceptor
- transfer can be measured in three ways
  - decrease in fluorescence intensity due to the presence of donor
  - decrease in the lifetime of the fluorescence
  - the acceptor absorbs the fluoresce 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 Eff= $1-(\tau_{D+A}/\tau_D)$
- The transfer is directly related to the distance (1-10nm)
- Eff= $r_o^6/(r_o^6+r^6)$ where r is the distance between donor and acceptor and r_o is the distance where 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



▶ FIGURE 10.18

Efficiency of energy transfer as a function of distance in dansyl-(L-prolyl)$_n$-α-naphthyl, n = 1 to 12. Energy transfer is 50% efficient at 3.46 nm. Solid line corresponds to r^{-6} dependence. (From Stryer and Haugland 1967, 719.)