

Investigation of Quantum Coherence in Biology

Quantum vibration effects on Sense of smell

By:
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Quantum biology refers to applications of quantum mechanics to biological objects and problems. Usually, it is taken to refer to applications of the "non-trivial" quantum features.



Are there any biological systems that use quantum mechanics to perform a task that either can not be done classically?



Do some organism take advantage of quantum mechanics to gain advantage over their competitors?



In what form do quantum effects in biology usually appear?

Schrodinger

genetic information was stored on an “aperiodic crystal” structure. He also speculated that quantum effects would lead to some sort of radically new behavior that would distinguish the living from the non-living.

Wigner

Enumerating the dimensionality of Hilbert space that the replication of an organism could not be described as a unitary quantum process.

von Neumann

the emergence of order from disorder in a system (e.g., the evolution of fitness in an organism) may be seen as a “win” in a “game” against nature

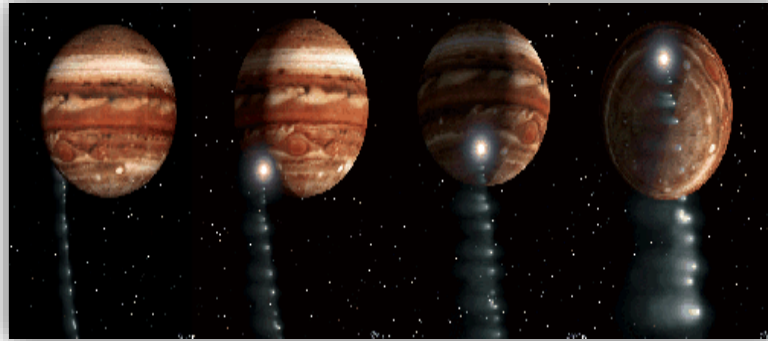
Bohr

What significance the results reached in the limited domain of physics may have for our views on the position of living organisms in the realm of natural science.

Vedral

living organisms might process information quantum mechanically, either at the bio-molecular level, or the cellular/neuronal level.

The Origin of Life



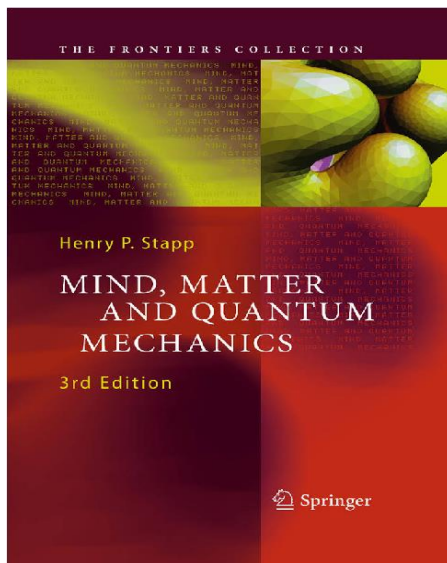
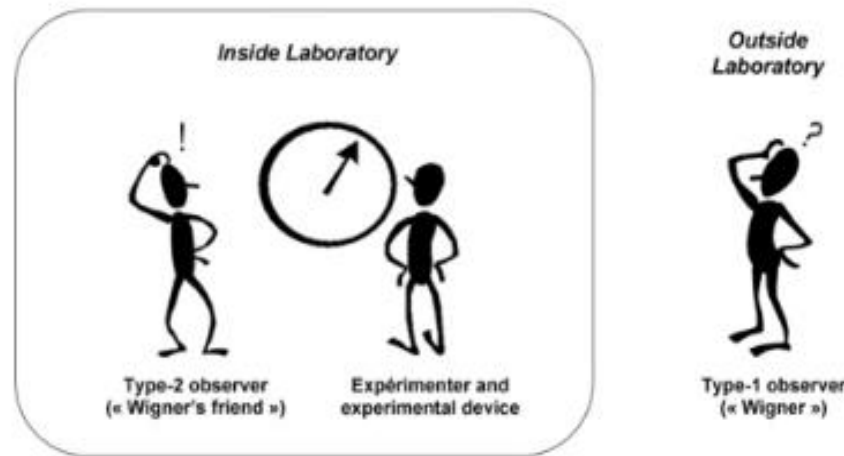
Biological complexity is distinguished by being *information based* complexity.

Is it conceivable that living systems exploit quantum information processing in some way, either to kick-start life, or to assist in its more efficient running?

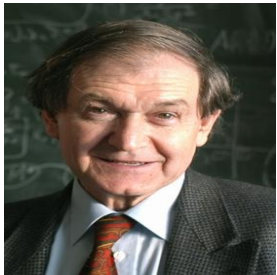
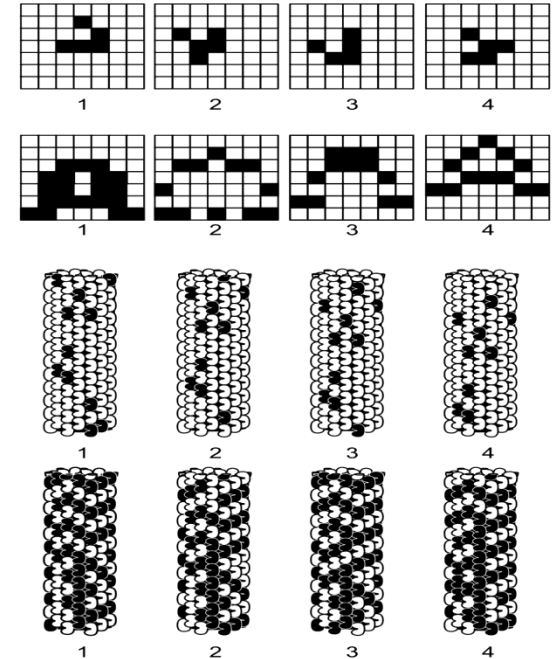
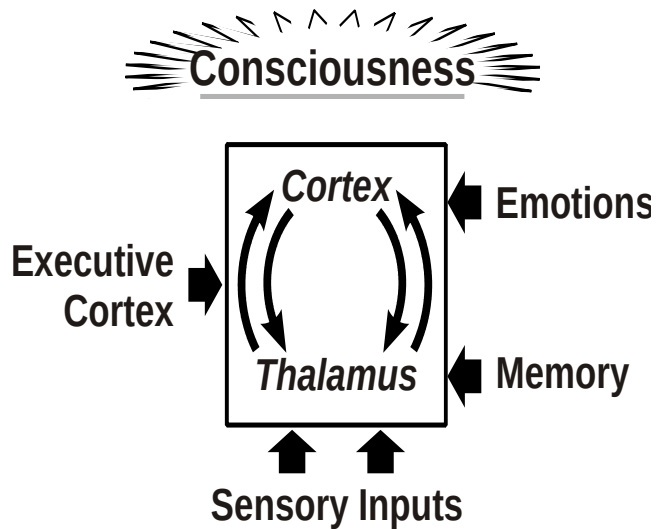
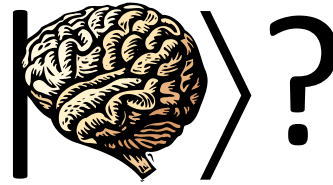
Vedral

living organisms might process information quantum mechanically, either at the bio-molecular level, or the cellular/neuronal level.

Quantum Consciousness



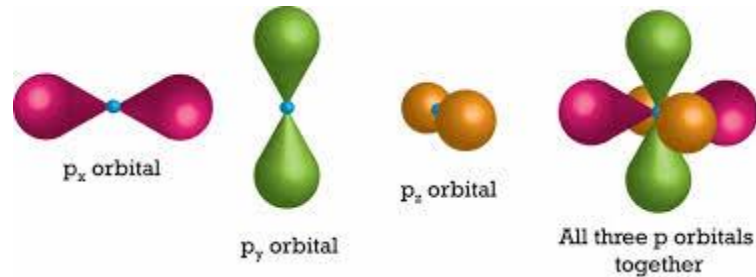
At a level at which conscious mental states and material brain states are distinguished, each conscious experience, according to Stapp (1999), has as its physical counterpart a quantum state reduction actualizing “the pattern of activity that is sometimes called the neural correlate of that conscious experience”.



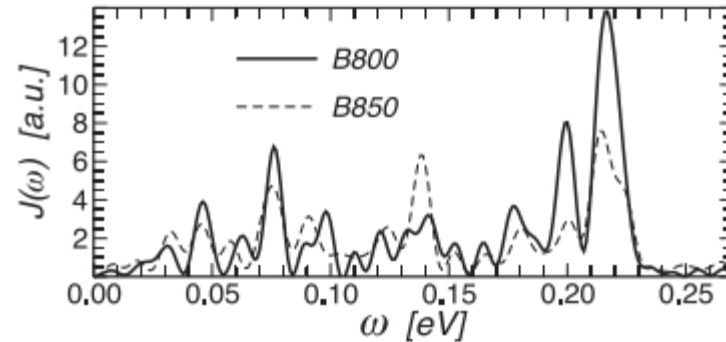
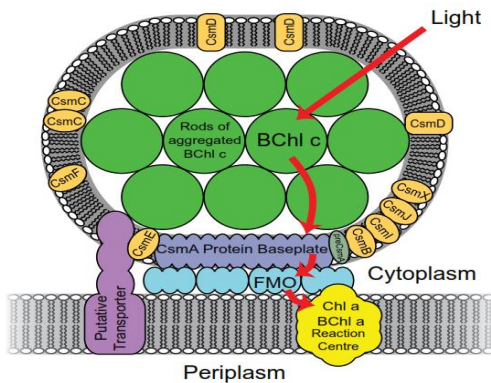
Consciousness is an actual physical process, a sequence of quantum state reductions connected by $E=h/t$ to an objective threshold inherent in spacetime geometry (objective reduction, OR)

Entanglement in Biology

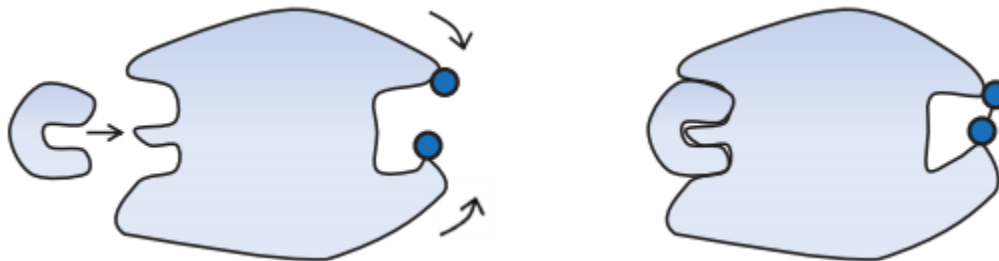
Entanglement of Basic Constituents



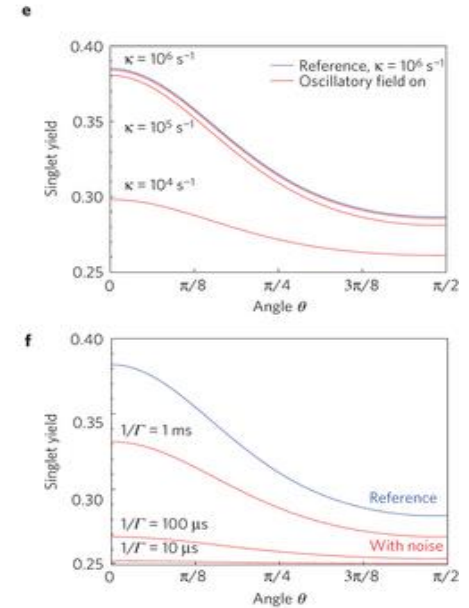
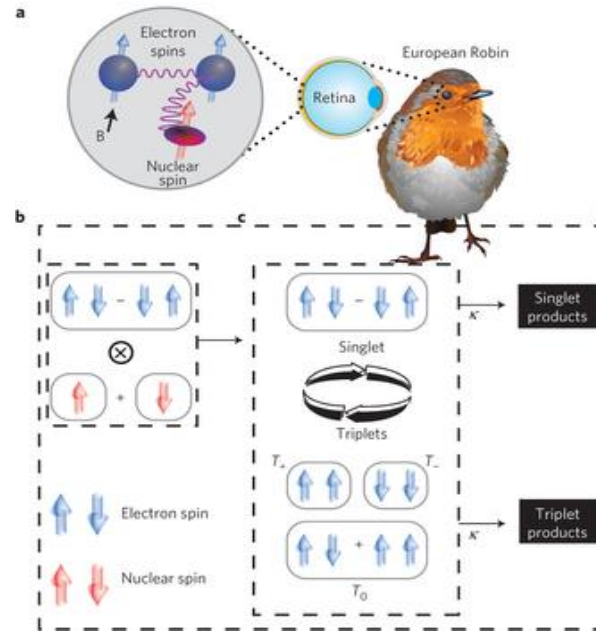
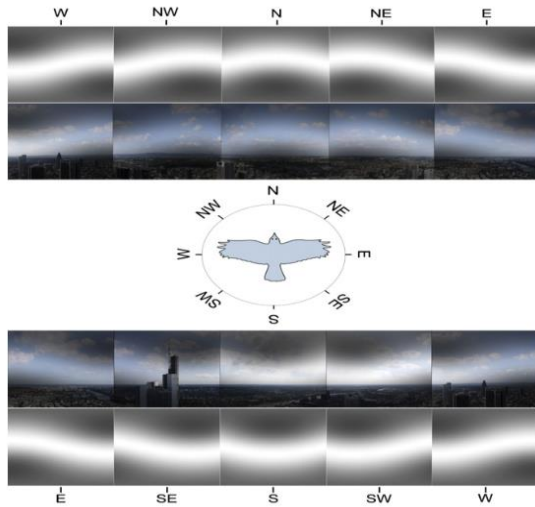
Dead Entanglement



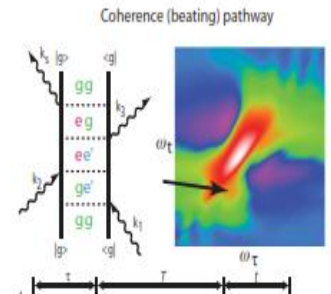
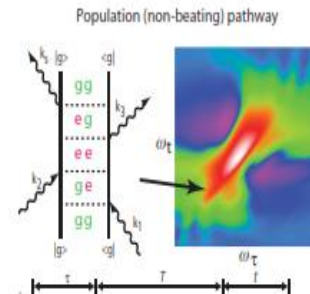
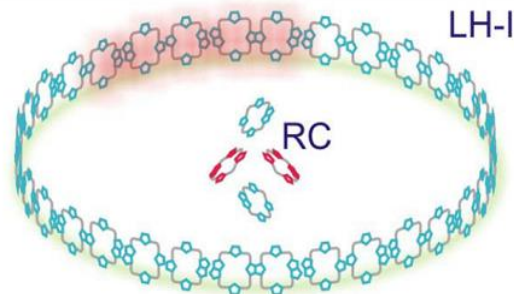
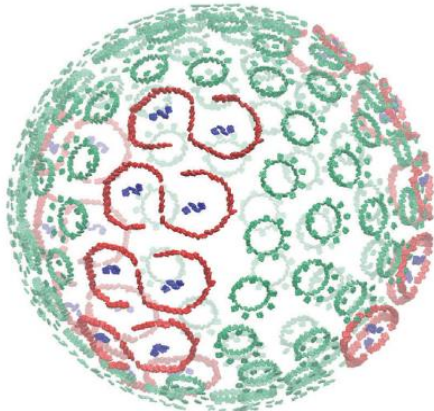
Live entanglement



Magneto Reception



Ultra Fast Quantum Dynamics in Photosynthesis



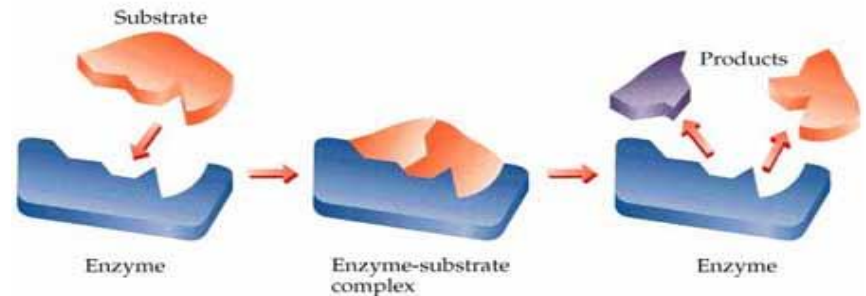
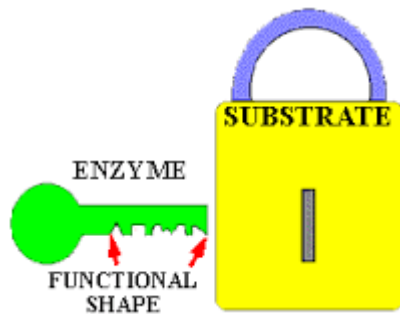
Olfaction

How do the receptors in our noses detect with such precision the odorant molecule?

Lock and Key Mechanism

To produce a particular scent a mutual fit is required between the odorant and receptor.

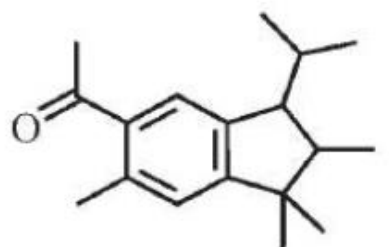
The idea is borrowed from the type of actions exhibited in enzyme behavior.



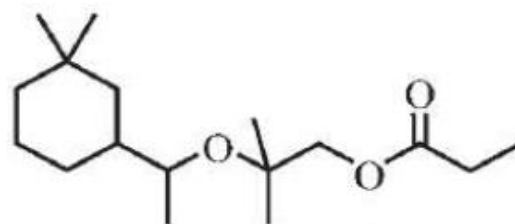
Odotope Theory

It may be one structural feature, such as a functional group, as opposed to the main body of the odorant, that a particular receptor responds to.

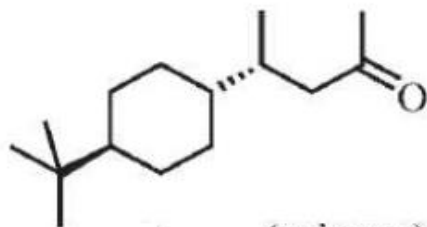
Shape of a molecule is important for the initial reception, though the receptor is not particular to exact fit.



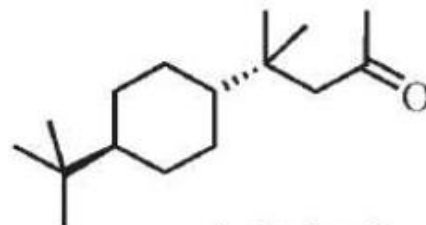
(musk)



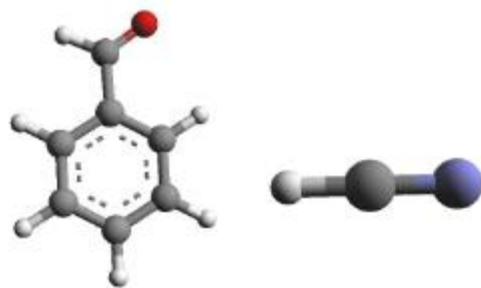
(musk)



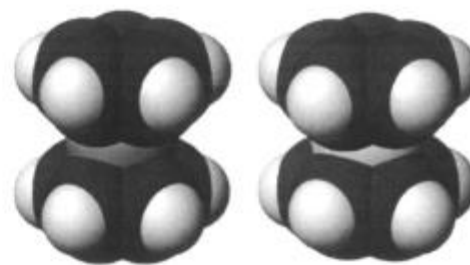
(urinous)



(odorless)



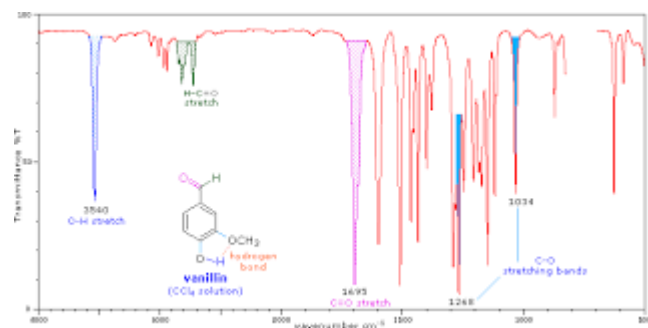
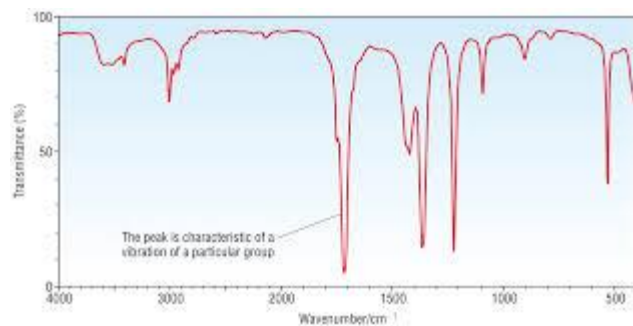
Smell the same



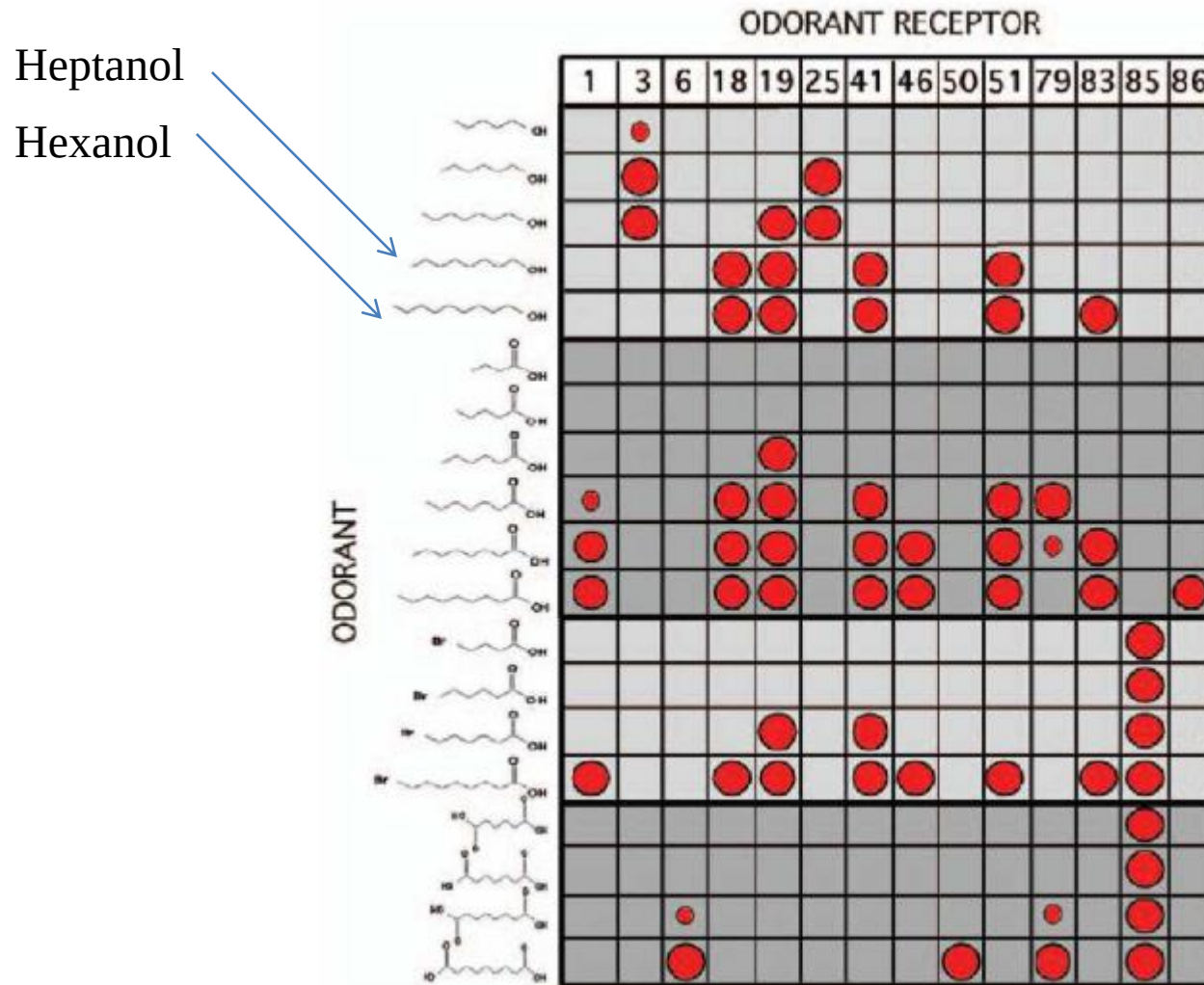
Smell different

Vibrational Theory

First proposed by Dyson (1938) and then Wright (1977) was that the signature of scent is due to a molecule's unique vibrational spectrum as opposed to its structure. Unique scents are attributed to a unique spectrum in the same way a color is associated to its frequency of light.



Smell is a combinatorial code

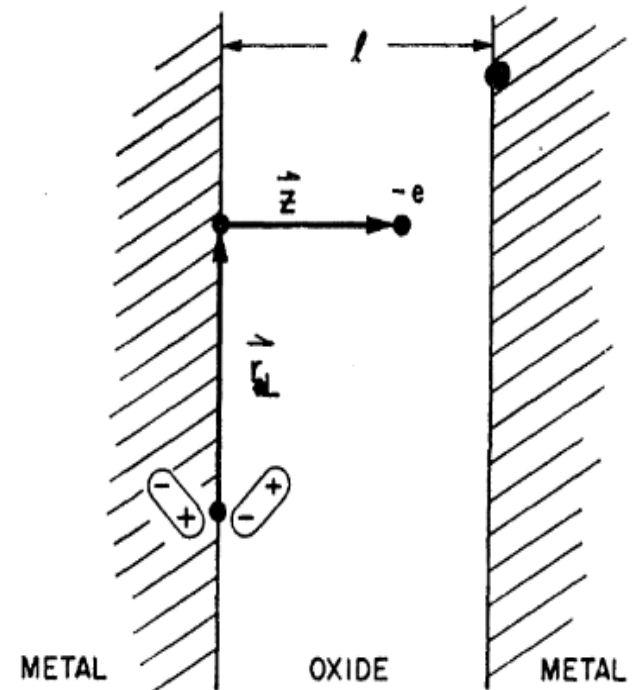
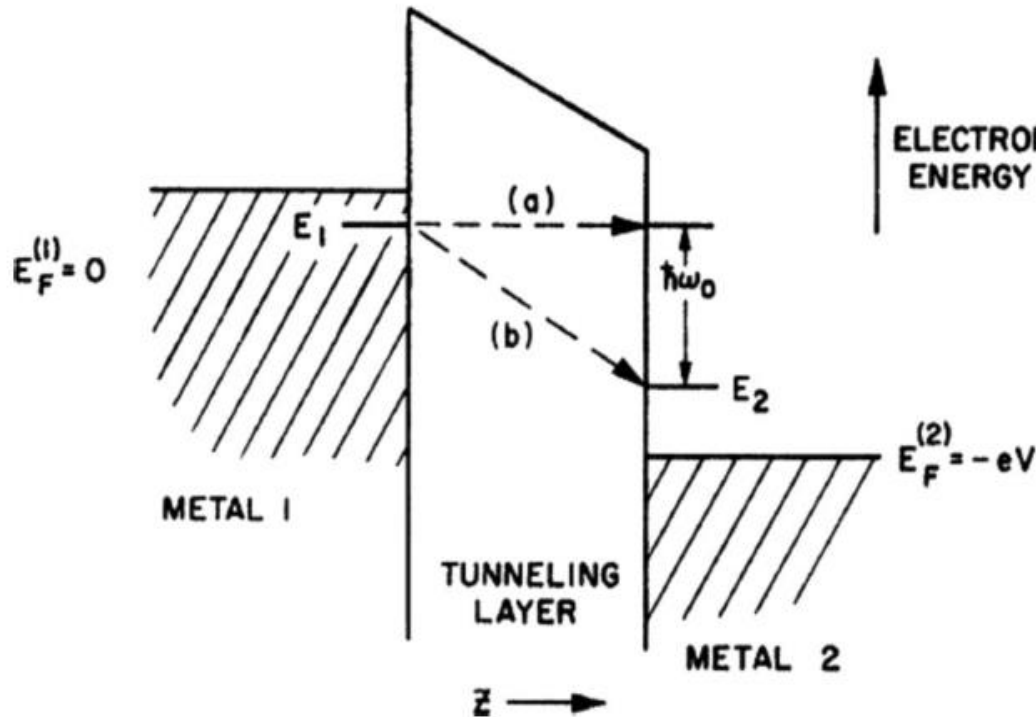


Ref: L.Buck: Unraveling the sense of smell –Nobel Lectures(2004)

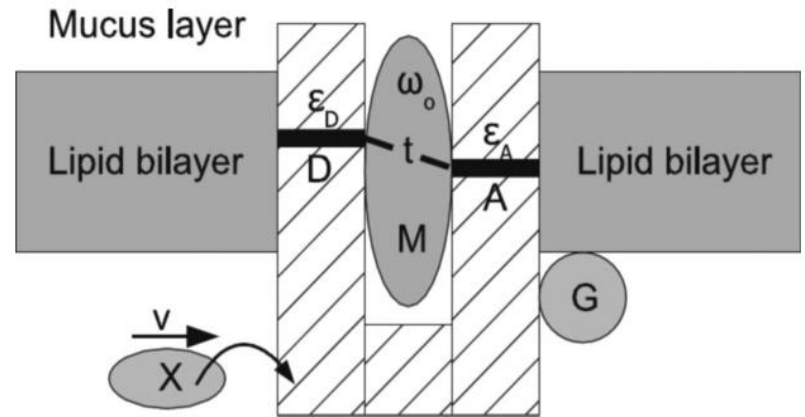
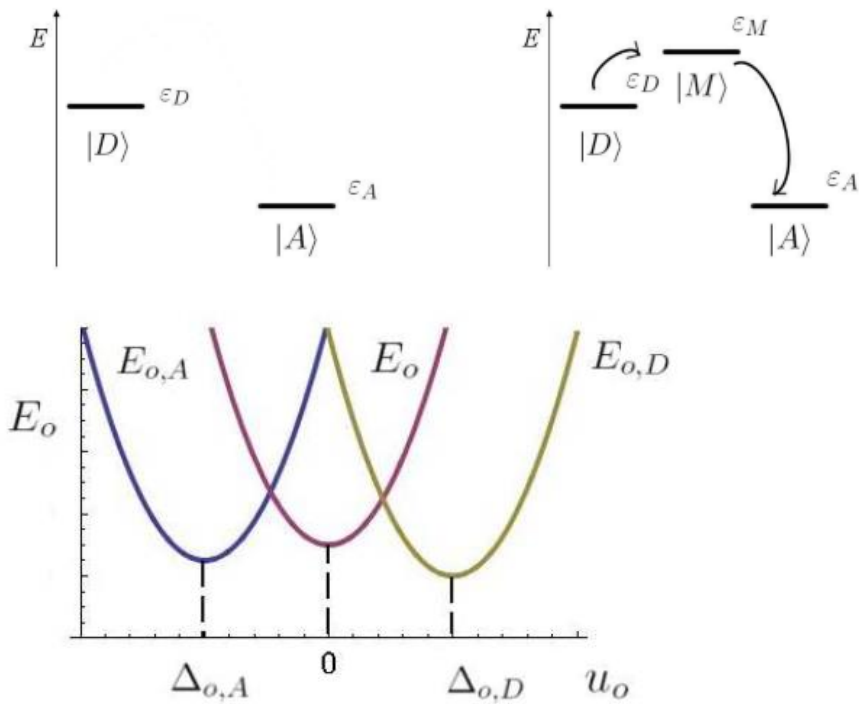
Odorant Vibrations

The nose is a 'spectrometer' and the signature of scent is due to a molecule's unique vibrational spectrum

Senses 1996, Turin proposes that the mechanism of detection is a form of 'biological inelastic electron tunneling' (IET).



Model



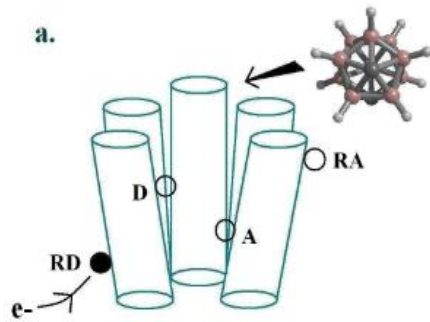
$$\frac{1}{D_{0 \rightarrow A,n}} = \frac{2\pi}{\hbar} |t|^2 \frac{\sigma_n}{(4\pi k_B T \lambda)^{\frac{1}{2}}} \exp\left(\frac{-(\varepsilon_D - \varepsilon_A - n\hbar\omega_0 - \lambda)^2}{4k_B T \lambda}\right)$$

$$\sigma_n = \frac{e^{-S} S^n}{n!}, S = \frac{\lambda}{\hbar \omega_0}$$

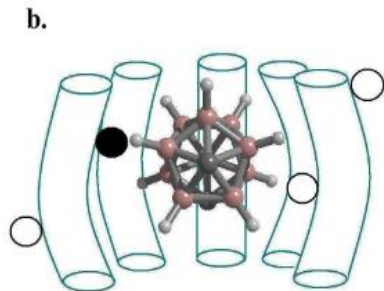
$$\lambda = \sum_q \hbar \omega_q S_q$$

Quantity	$\hbar\omega$	S	λ	$ t $
Value	200 meV	0.1	30 meV	1 meV

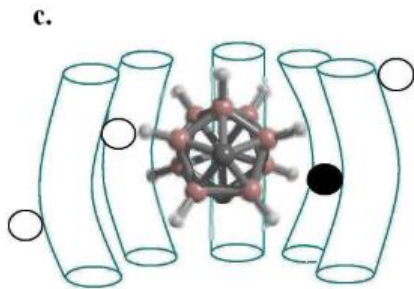
$$\tau_{T_0}=87\text{ ns} \quad \tau_{T_1}=0.15\text{ ns}$$



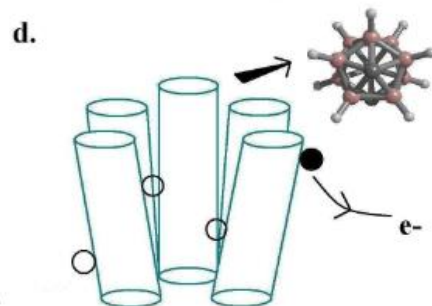
M approaches R meanwhile an electron diffuses to RD position.



M docks at the LBD the overall configuration of R+M changes



The electron jumps from D to A causing M to vibrate.



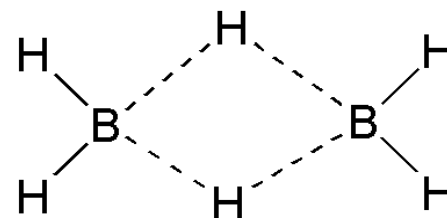
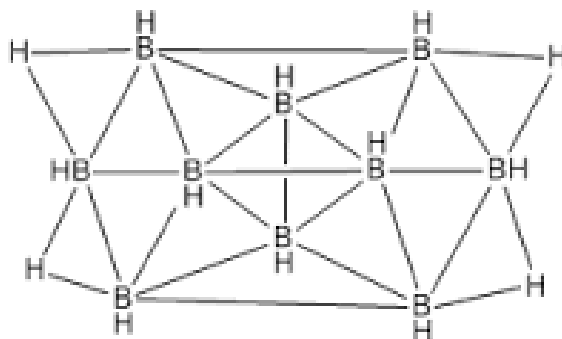
Signal transduction is initiated with the G-Protein release.

Evidences for Tunneling in Nasal System

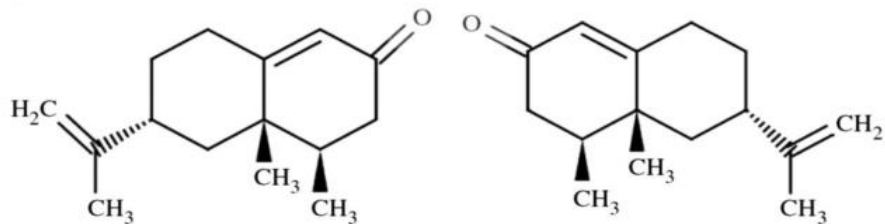
For further support on isotopic substitution in a range of benzaldehydes, Haffenden et al. show by sensory analysis and IR spectra that certain shifts in the vibrational modes correspond to an alteration in scent. *Drosophila* not only discriminates isotopes, but ignores the uncommon (unnatural) isotope.



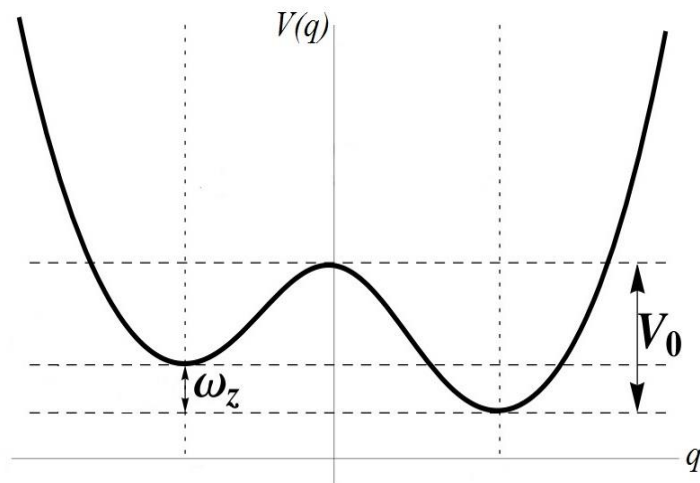
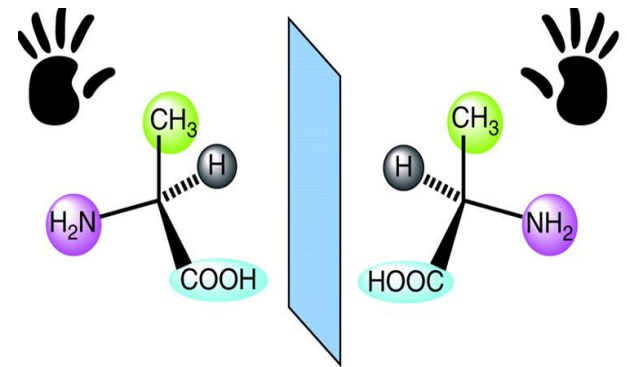
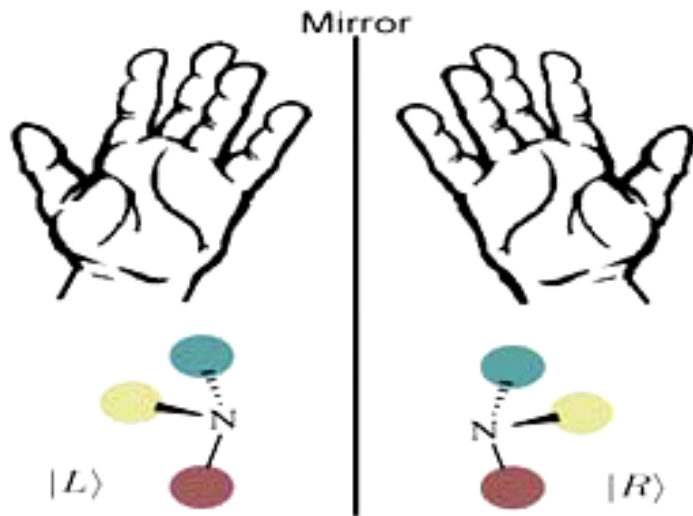
H₂S and decaborans smell sulfuraceous. Carborans smell camphoraceous. The sulfuraceous smell of H₂S is associated with vibrations in the region of 2600 1/cm. In this region decaborane has IR couplings that are one to two orders of magnitude greater than the carboranes.



The vibration-based theories of olfaction are commonly refused on the grounds that enantiomers of chiral odorants have the same vibrational spectra but different smells

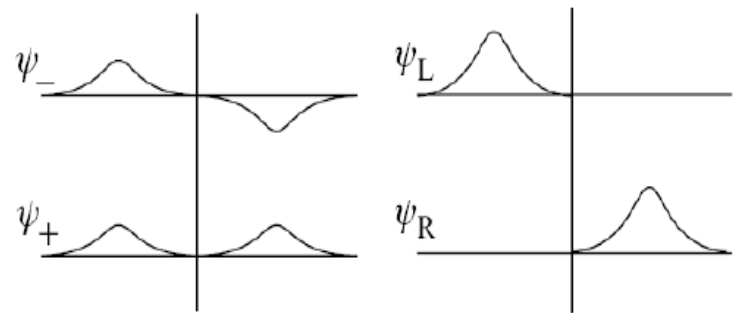


Enantiomers exemplify the importance of shape in receptor detection.



$$H = - \begin{pmatrix} \omega_z & \delta \\ \delta & -\omega_z \end{pmatrix}$$

$$|1\rangle = \sin \frac{\theta}{2} |L\rangle + \cos \frac{\theta}{2} |R\rangle, \quad |2\rangle = \cos \frac{\theta}{2} |L\rangle - \sin \frac{\theta}{2} |R\rangle$$



Dissipative vibrational model for chiral recognition in olfaction

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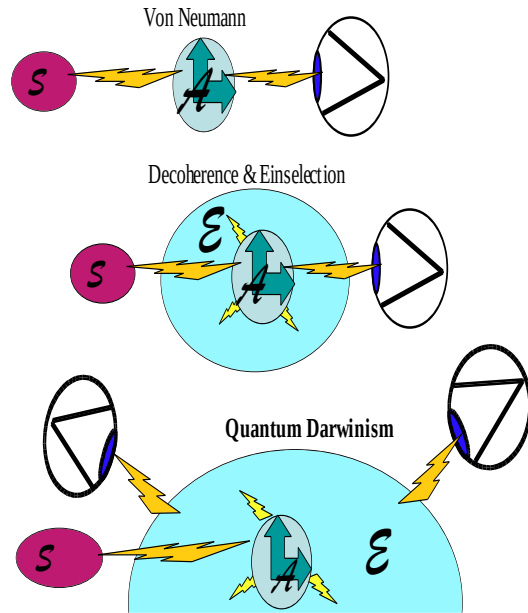
¹*Foundations of Physics Group, School of Physics, Institute for Research in Fundamental Sciences (IPM), P. O. Box 19395-5531, Tehran, Iran*

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We examine the olfactory discrimination of left- and right-handed enantiomers of chiral odorants based on the odorant-mediated electron transport from a donor to an acceptor of the olfactory receptors embodied in a biological environment. The chiral odorant is effectively described by an asymmetric double-well potential whose minima are associated to the left- and right-handed enantiomers. The introduced asymmetry is considered an overall measure of chiral interactions. The biological environment is conveniently modeled as a bath of harmonic oscillators. The resulting spin-boson model is adapted by a polaron transformation to derive the corresponding Born-Markov master equation with which we obtain the elastic and inelastic electron tunneling rates. We show that the inelastic tunneling through left- and right-handed enantiomers occurs with different rates. The discrimination mechanism depends on the ratio of tunneling frequency to localization frequency.

Einselection



$$|\psi_{\pm}\rangle = \frac{1}{\sqrt{2}} \left(|\psi_1\rangle |E_1\rangle \pm |\psi_2\rangle |E_2\rangle \right)$$

$$\frac{1}{\sqrt{2}} (|\psi_+\rangle + |\psi_-\rangle) = |\psi_1\rangle |E_1\rangle$$

- Classical Properties of the Quantum system are in correspondence with pointer states.
- Pointer states are robust against entanglement with the environment.

W. H. Zurek, Decoherence and the transition from quantum to classical, *Phys.Today*, **1991**, 44, 36–44.

W. H. Zurek, Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse?, *Phys. Rev. D*, **1981**, 24, 1516–1525.

Formalism

$$\hat{H}_e = \varepsilon_D |D\rangle\langle D| + \varepsilon_A |A\rangle\langle A|$$

$$\hat{H}_o = -\frac{\delta}{2} \hat{\sigma}_x - \frac{\omega_z}{2} \hat{\sigma}_z$$

$$\hat{H}_\varepsilon = \sum_i \omega_i \hat{b}_i^\dagger \hat{b}_i$$

$$\hat{H}_{\text{int}} = \Delta \left(|A\rangle\langle D| + |D\rangle\langle A| \right) + \left(\gamma_D |D\rangle\langle D| + \gamma_A |A\rangle\langle A| \right) \otimes \hat{\sigma}_x +$$

$$\sum_i \left(\gamma_{D,i} |D\rangle\langle D| + \gamma_{A,i} |A\rangle\langle A| \right) \otimes \left(\hat{b}_i + \hat{b}_i^\dagger \right)$$

$$\hat{U} = \exp \left[\frac{i}{2} \left(\lambda' |D\rangle\langle D| - \lambda |A\rangle\langle A| \right) \hat{\sigma}_y \right] \exp \left[\sum_i \left(\frac{\lambda_{iD}}{\omega_i} |D\rangle\langle D| + \frac{\lambda_{iA}}{\omega_i} |A\rangle\langle A| \right) \left(\hat{b}_i - \hat{b}_i^\dagger \right) \right]$$

$$\tilde{H}_0 = \left(\varepsilon_D + \mu' \hat{\sigma}_z \right) |D\rangle\langle D| + \left(\varepsilon_A + \mu \hat{\sigma}_z \right) |A\rangle\langle A| + \sum_i \omega_i \hat{b}_i^\dagger \hat{b}_i$$

$$\tilde{\tilde{H}}_{\text{int}} = \Delta \left[|A\rangle\langle D| e^{\frac{i}{2}(\lambda + \lambda') \hat{\sigma}_y} \hat{F}^+ + |D\rangle\langle A| e^{\frac{-i}{2}(\lambda + \lambda') \hat{\sigma}_y} \hat{F}^- \right]$$

$$\hat{F}^\pm = e^{\pm \sum_i \left(\frac{\gamma_{iD} - \gamma_{iA}}{\omega_i} \right) \left(\hat{b}_i^\dagger - \hat{b}_i \right)}$$

$$\partial_t \rho(t) = - \int_0^t dt' \text{Tr}_\varepsilon \left[\tilde{H}_{\text{int}}(t), \left[\tilde{H}_{\text{int}}(t'), \hat{\rho}_{s\varepsilon}(t') \right] \right]$$

$$\hat{\rho}(t) = \sum_{i,j;x,x'} \rho_{i,j;x,x'} |i,x\rangle\langle j,x'| \quad i,j \in A,D \quad x,x' \in i,j$$

$$\Gamma_{DiAj} = 2\Delta^2 \Re \int_0^\infty d\tau \{C(\tau) e^{i\varepsilon\tau} \langle f | \hat{\Xi}(\tau) | i \rangle \langle i | e^{-\frac{i}{2}(\lambda+\lambda')\hat{\sigma}_y} | j \rangle \}.$$

$$C(\tau) = C^*(-\tau) = tr_E \{ \hat{F}_\pm(-\tau) \hat{F}_\mp(0) \} = e^{-\{v(\tau) + i\eta(\tau)\}},$$

$$v(\tau) = \int_0^\infty d\omega \frac{J(\omega)}{\omega^2} \left[\sin^2 \left(\frac{\omega\tau}{2} \right) \coth \left(\frac{\omega}{2k_B T} \right) \right]$$

$$\eta(\tau) = \int_0^\infty d\omega \frac{J(\omega)}{\omega^2} \sin(\omega\tau).$$

$$\Gamma_{\text{DLA2}} \approx \cos\left(\frac{\lambda+\lambda'-\theta}{2}\right) \sin\left(\frac{\lambda+\lambda'}{2}\right) \sin\left(\frac{\theta}{2}\right)$$

$$\times \frac{\sqrt{\pi}\Delta^2}{\sqrt{k_B T J_\circ \Lambda}} \exp\left\{\frac{-[\varepsilon+(\mu+\mu')-\Lambda]}{4k_B T J_\circ \Lambda}\right\}$$

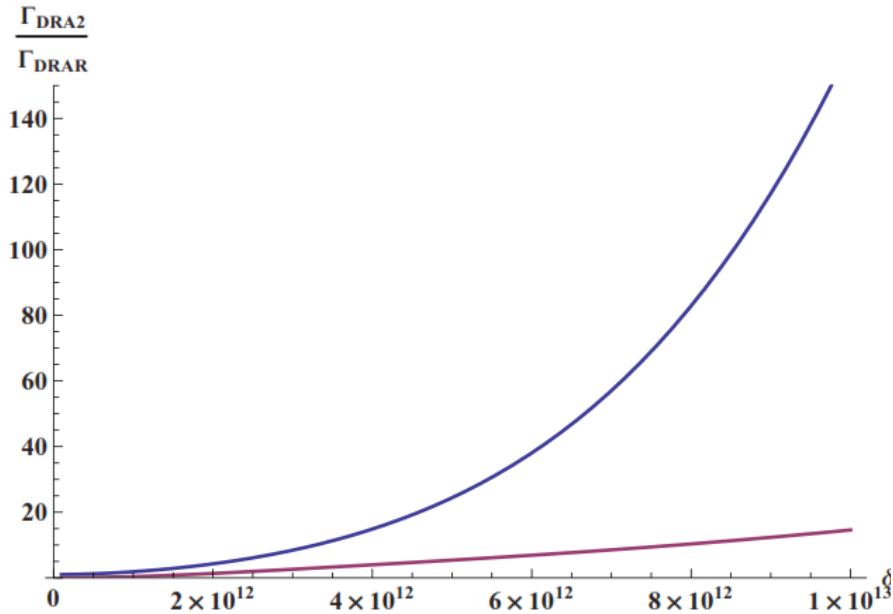
$$\Gamma_{\text{DRA2}} \approx \sin\left(\frac{\lambda+\lambda'-\theta}{2}\right) \sin\left(\frac{\lambda+\lambda'}{2}\right) \cos\left(\frac{\theta}{2}\right)$$

$$\times \frac{\sqrt{\pi}\Delta^2}{\sqrt{k_B T J_\circ \Lambda}} \exp\left\{\frac{-[\varepsilon-(\mu+\mu')-\Lambda]}{4k_B T J_\circ \Lambda}\right\}$$

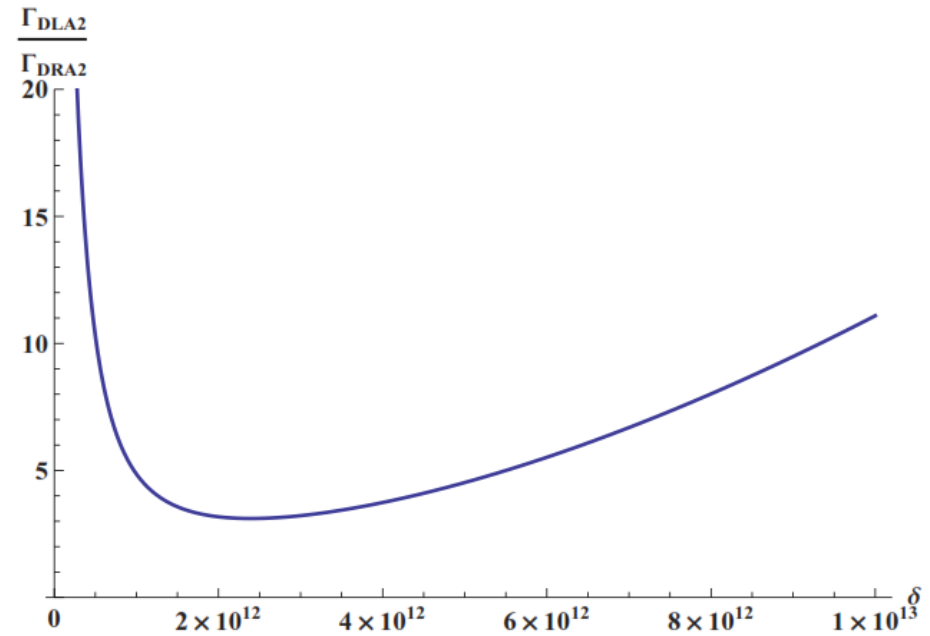
$$\Gamma_{\text{DiAi}} = \cos^2\left(\frac{\lambda+\lambda'}{2}\right) \frac{\sqrt{\pi}\Delta^2}{\sqrt{k_B T J_\circ \Lambda}} \exp\left\{\frac{-(\varepsilon-\Lambda)}{4k_B T J_\circ \Lambda}\right\}$$

Parameter	Value	Parameter	Value
ε	$\sqrt{\delta^2 + \omega_z^2}$	J_{O}	1
Δ	$0.01\sqrt{\delta^2 + \omega_z^2}$	Λ	10^{12} Hz
$\gamma_D(= -\gamma_A)$	$0.1\sqrt{\delta^2 + \omega_z^2}$	T	300 K

$$\tau_{T_0} = 80 \text{ ns} \quad \tau_{T_1} = 0.77 \text{ ns}$$

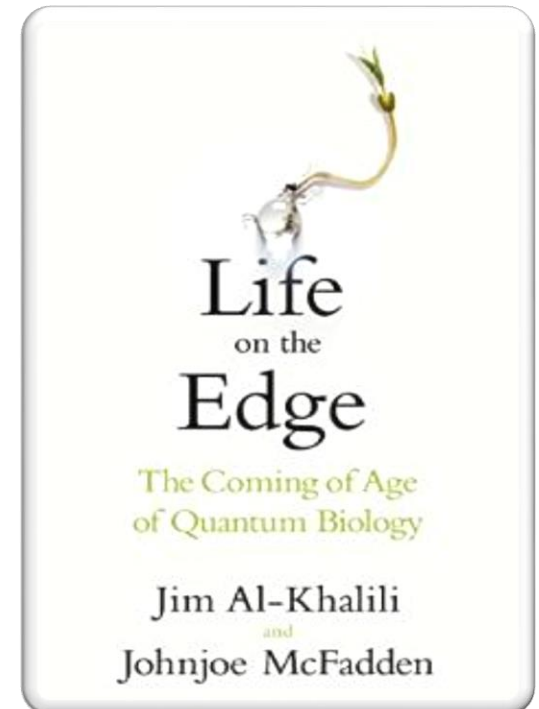
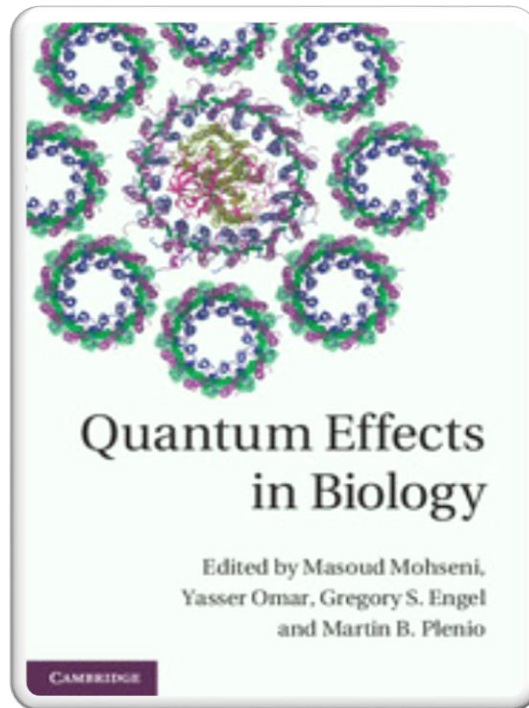
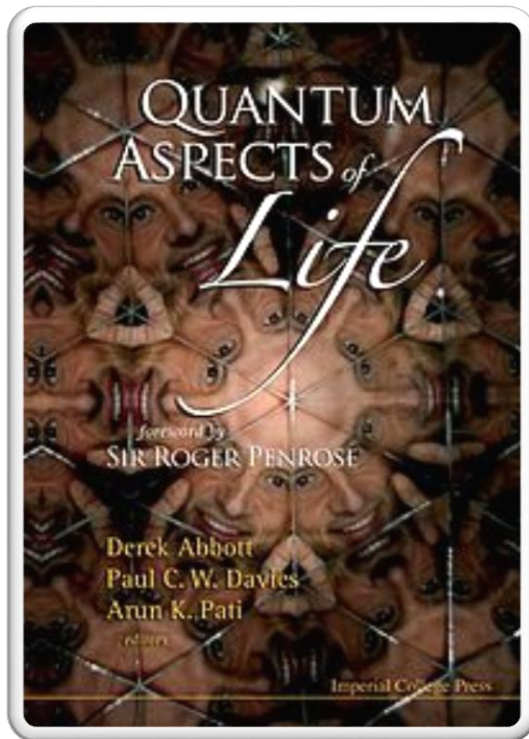


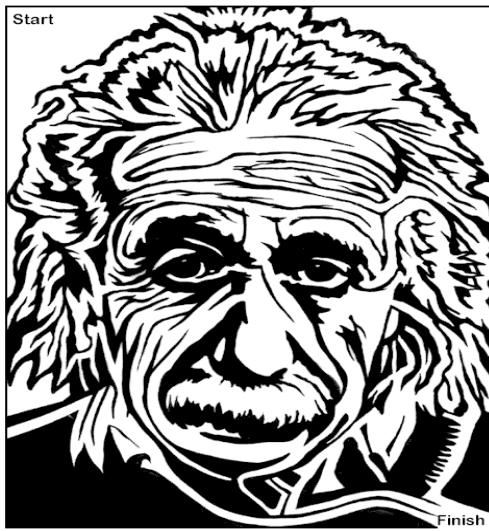
The ratio of inelastic rate to elastic rate versus the tunneling frequency δ for the left-handed enantiomer (blue) and the right-handed enantiomer (red) at $\omega_z = 10^{12}$ Hz.



The ratio of inelastic rates for the left-handed enantiomer Γ_{DLA2} to the right-handed enantiomer Γ_{DRA2} versus the tunneling frequency δ at $\omega_z = 10^{12}$ Hz.

Some references



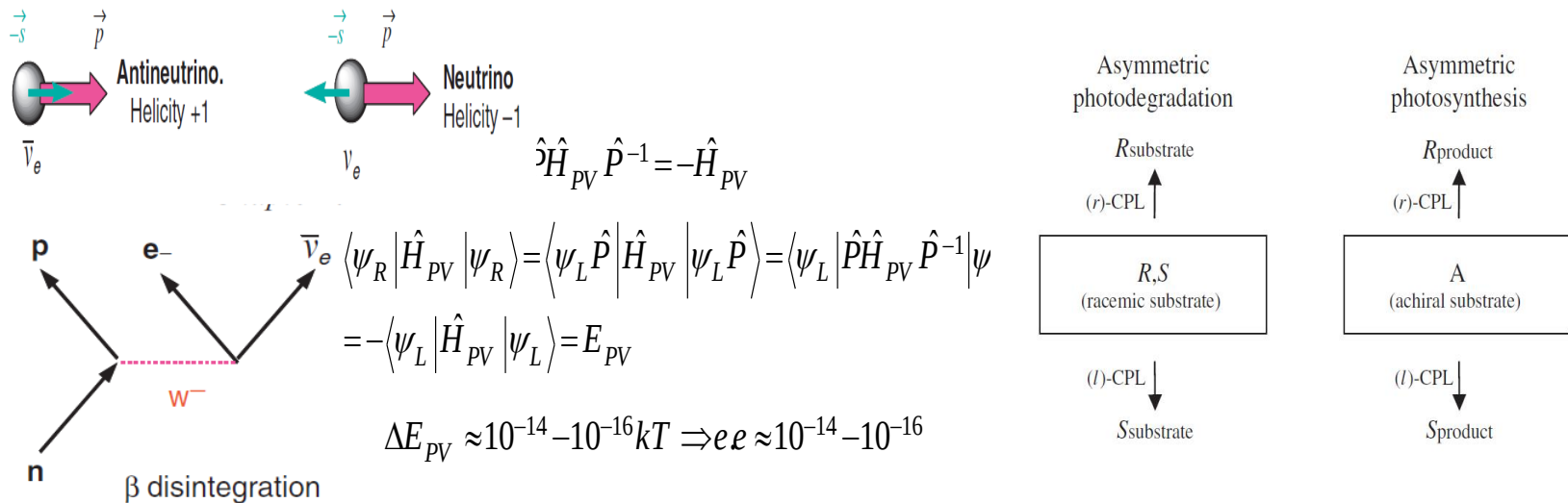
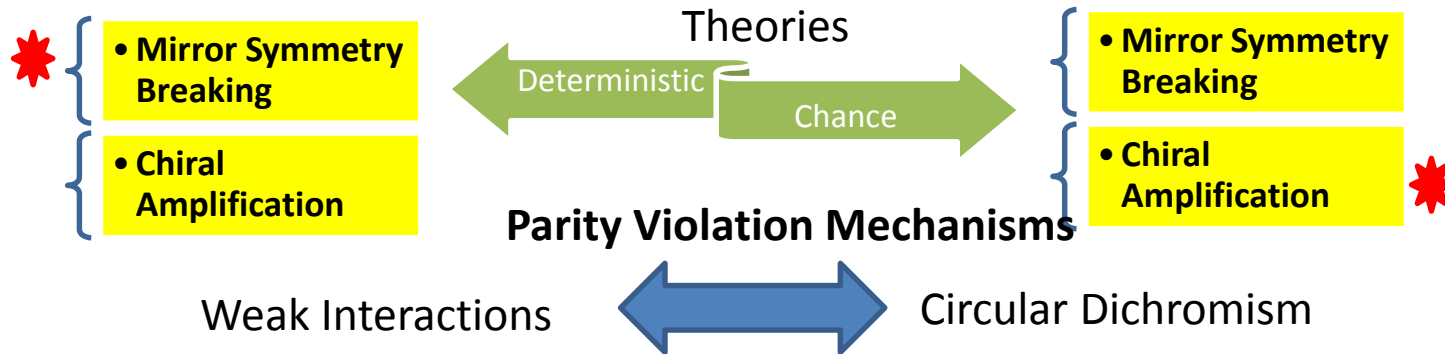


One can best feel in dealing with living thing how primitive physics still is.

Thanks for your consideration



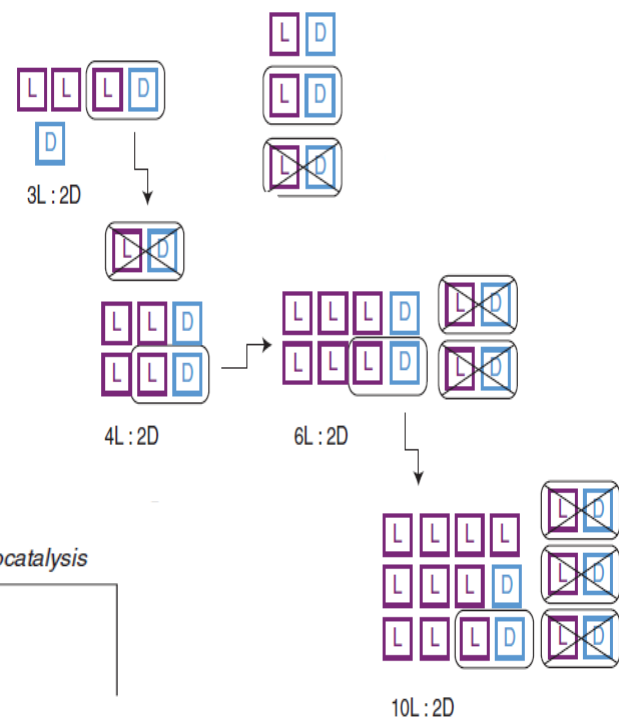
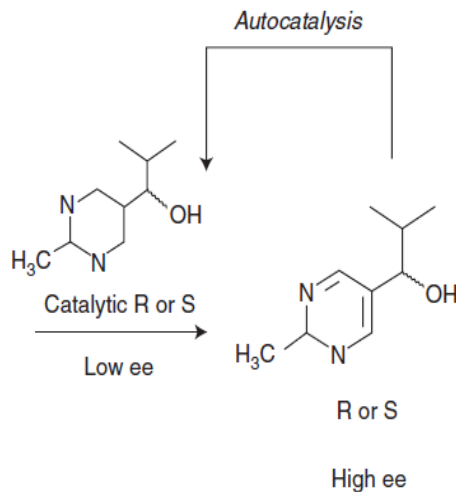
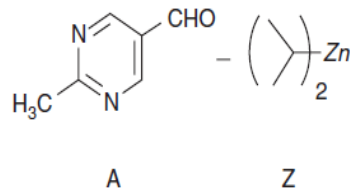
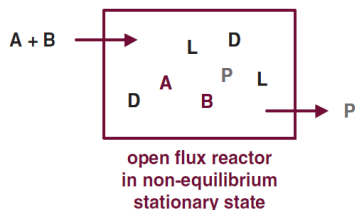
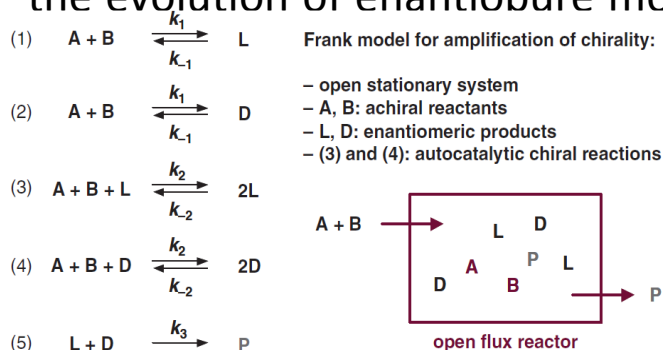
Theories on the Origin of Homochirality



Amplifying the Imbalance

Chemical Model

➔ The model is based on a simple idea: a substance that acts as a catalyst in its own self-production and at the same time acts to suppress synthesis of its enantiomer enables the evolution of enantiopure molecules from a



F. C. Frank, Biochem. Biophys. Acta., 1953, 11, 459–463.

