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QUANTUM ENTANGLEMENT IN AVIAN NAVIGATION

Ministerstwo Nauki
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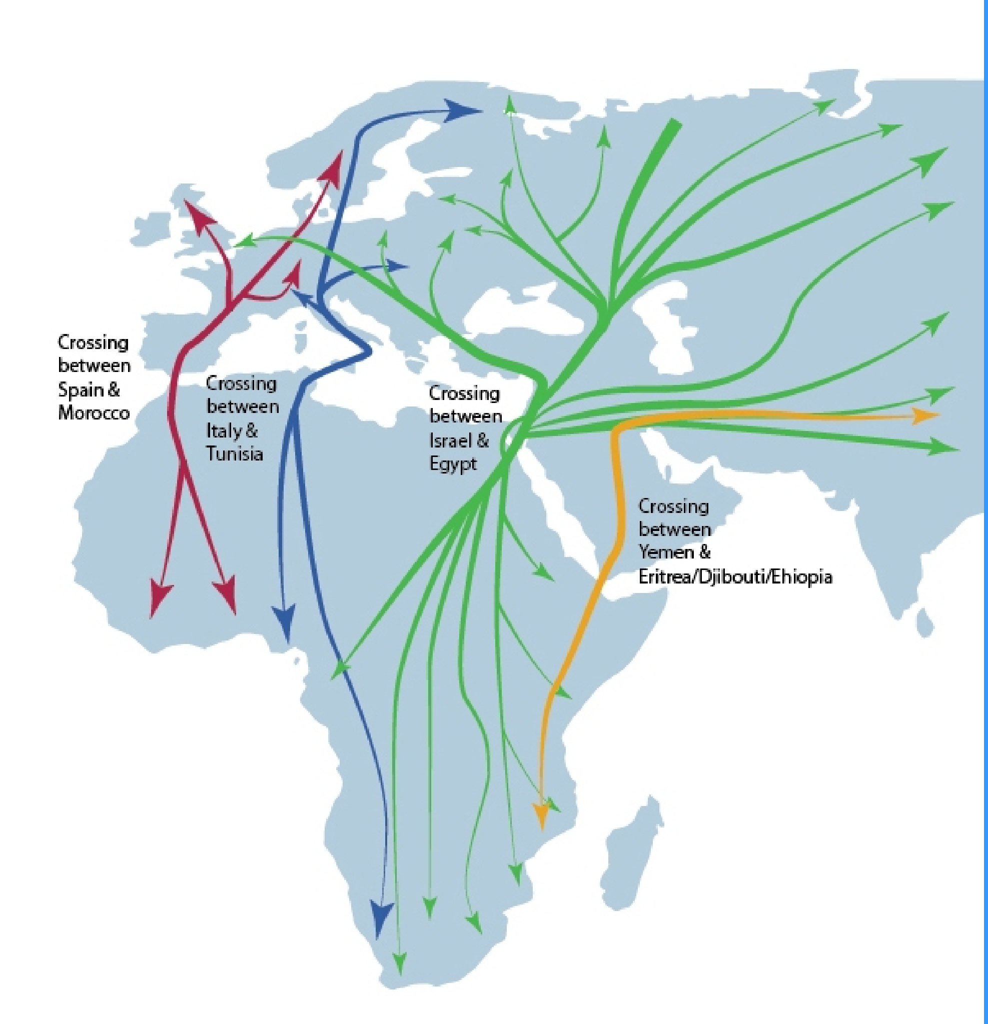
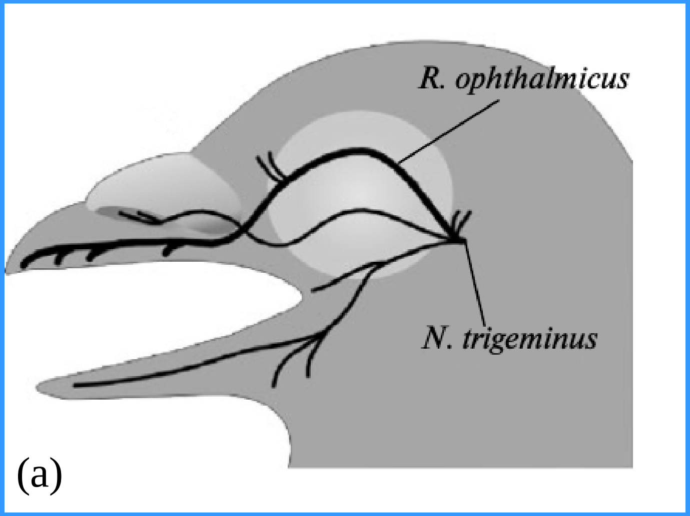
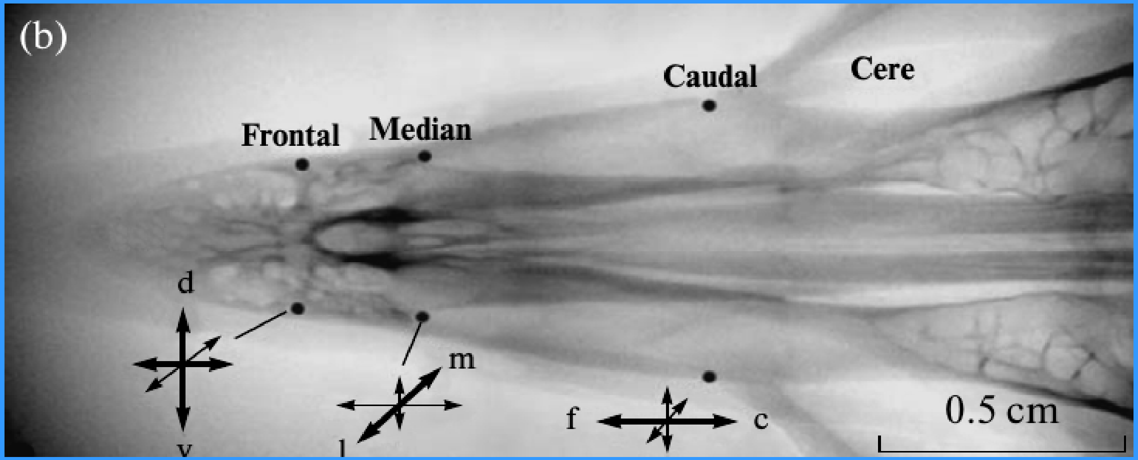
Erithacus rubecula

The mechanism of in-flight navigation during the seasonal movement of migratory birds has been puzzling researchers for a long time. At present, there is a prevailing opinion that there are two types of magnetodetection: based on iron-containing structures in the beaks like for a homing pigeon or based on a chemical sensor in the bird’s eye like for the European Robin





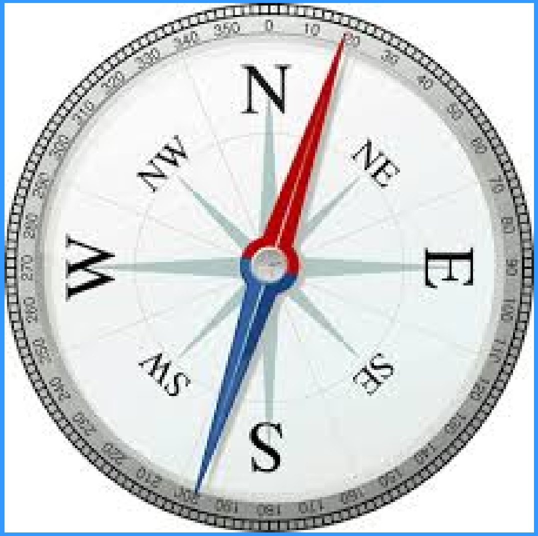
In 2007 the iron-containing subcellular particles of maghemite and magnetite were found in sensory dendrites of the skin lining the upper beak of homing pigeons.



Model of ironbased magnetoreceptor. Localisation of putative ironcontaining magnetoreceptors in the upper beak of homing pigeons. (a) Schematic drawing of pigeon head with the ophthalmic branch of thetrigeminal nerve. (b) X-ray image of the pigeon upper beak.

Some birds are sensitive even to rapidly fluctuating artificial fields (radio-frequency magnetic fields in the MHz range). The key is that these fields had no effect on magnetic materials such as magnetite. It indicates that the avion navigation does not need to be based on simple chunks of magnetic material in bird beaks.

Moreover, the magnetic compass of birds works in a way that is very different from our technical compass: it is an inclination compass that ignores polarity and instead relies on the course of the field lines and their inclination.

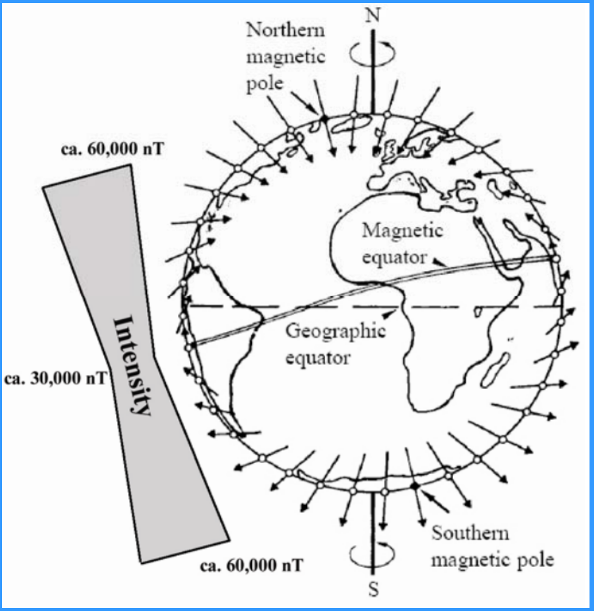


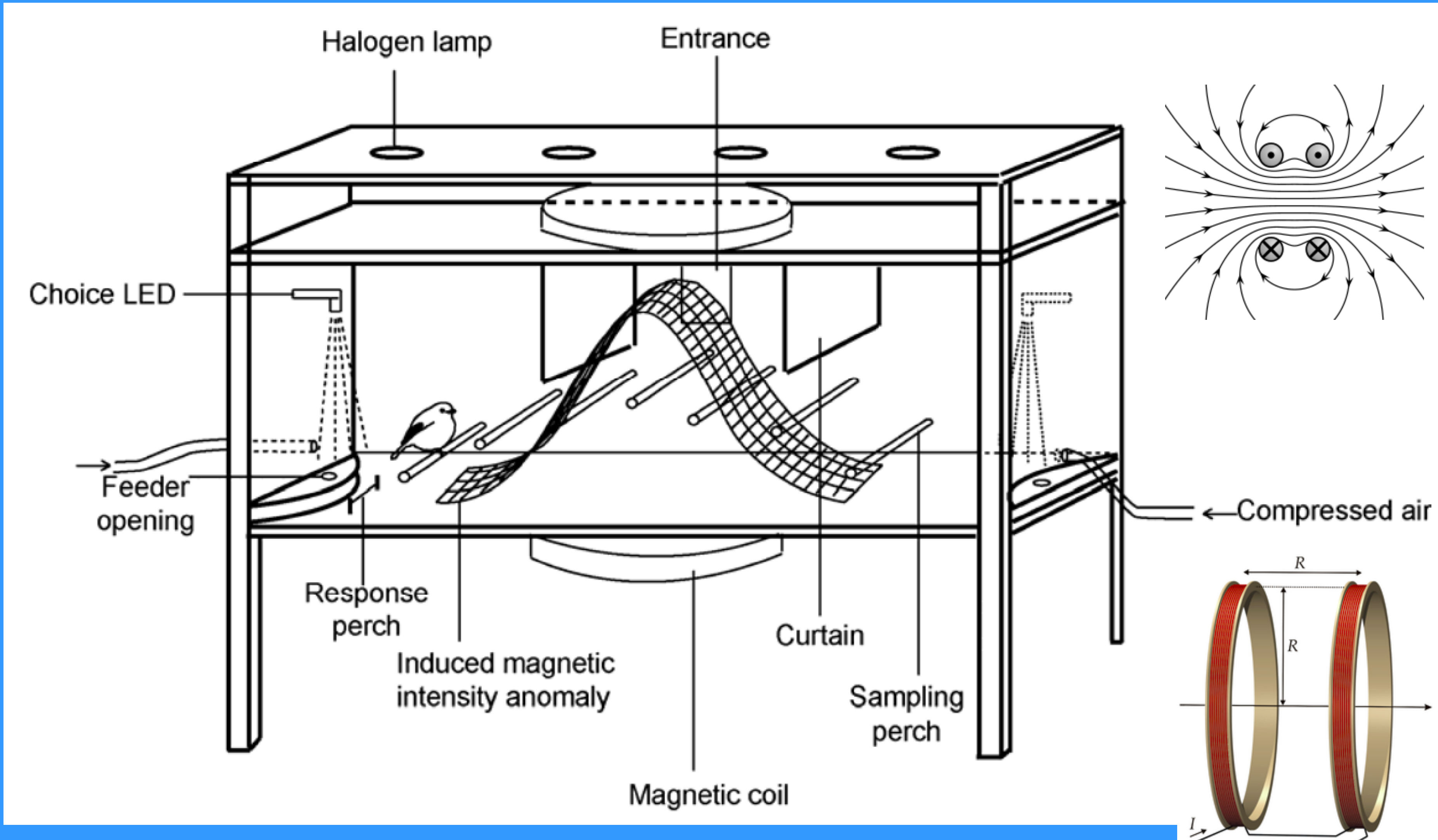
Magnetic Compass of European Robins

Wolfgang Wiltschko; Roswitha Wiltschko

Science, New Series, Vol. 176, No. 4030 (Apr. 7, 1972), 62-64.

There is experimental evidence the European Robin, every autumn migrating from Sweden to the Mediterranean, using magneto-reception to navigate, exploits the quantum correlations to navigate in Earth magnetic field. The ratio of Earth magnetic field energy to thermal energy is about $\mu_B 60\mu T/k_B\ 310K \approx 10^{-8}$, so the signal is extremely low. It is worth noting, European Robins derive their north direction from interpreting the inclination of the axial direction of the magnetic field lines inspace, and they take the direction on the magnetic north-south axis for „north" where field lines and gravity vector form the smaller angle.





The direction that birds selected in Kramer cages can be modified by changing the direction of the magnetic field, in closed rooms as well as outdoors. The magnetic field was produced with Helmholtz coil (2 m in diameter).

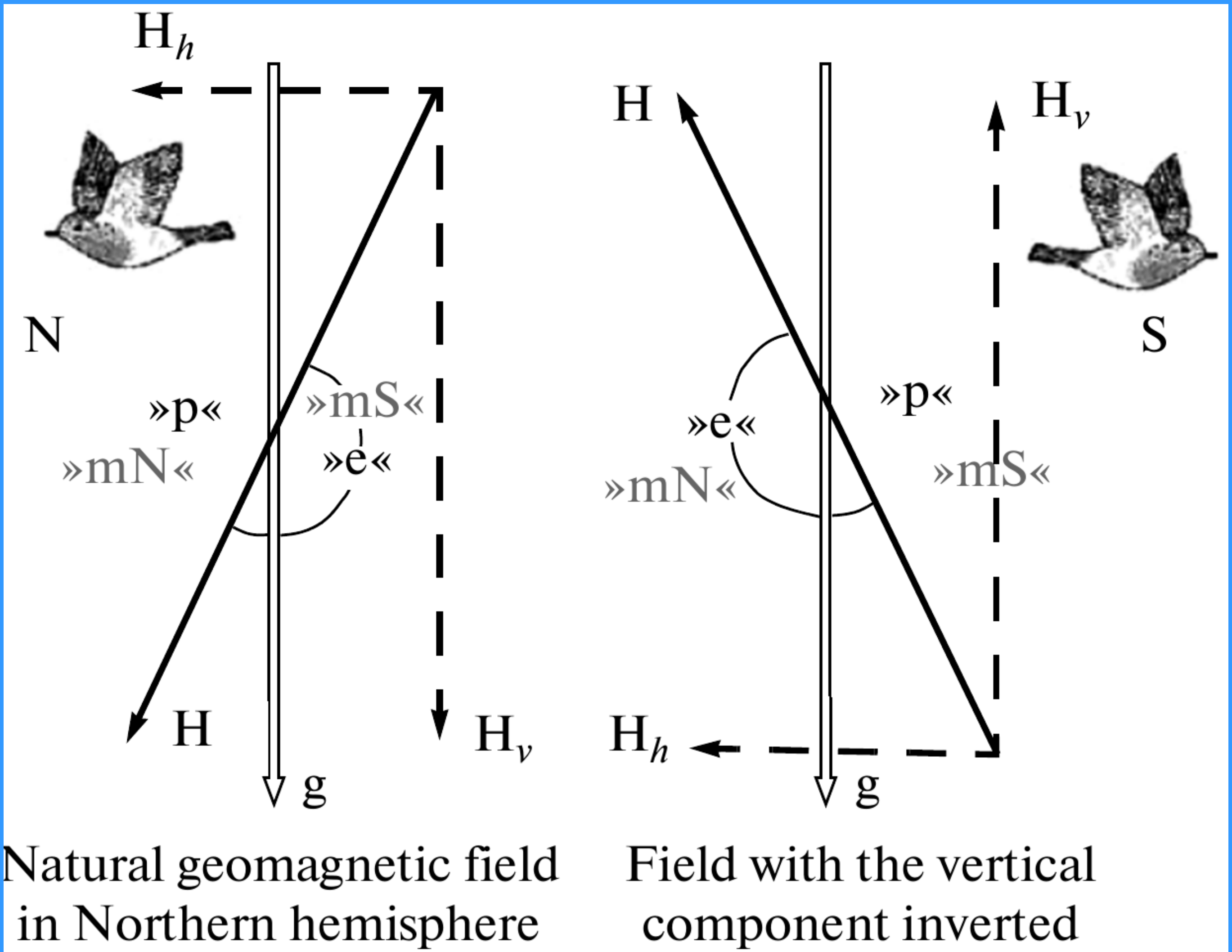
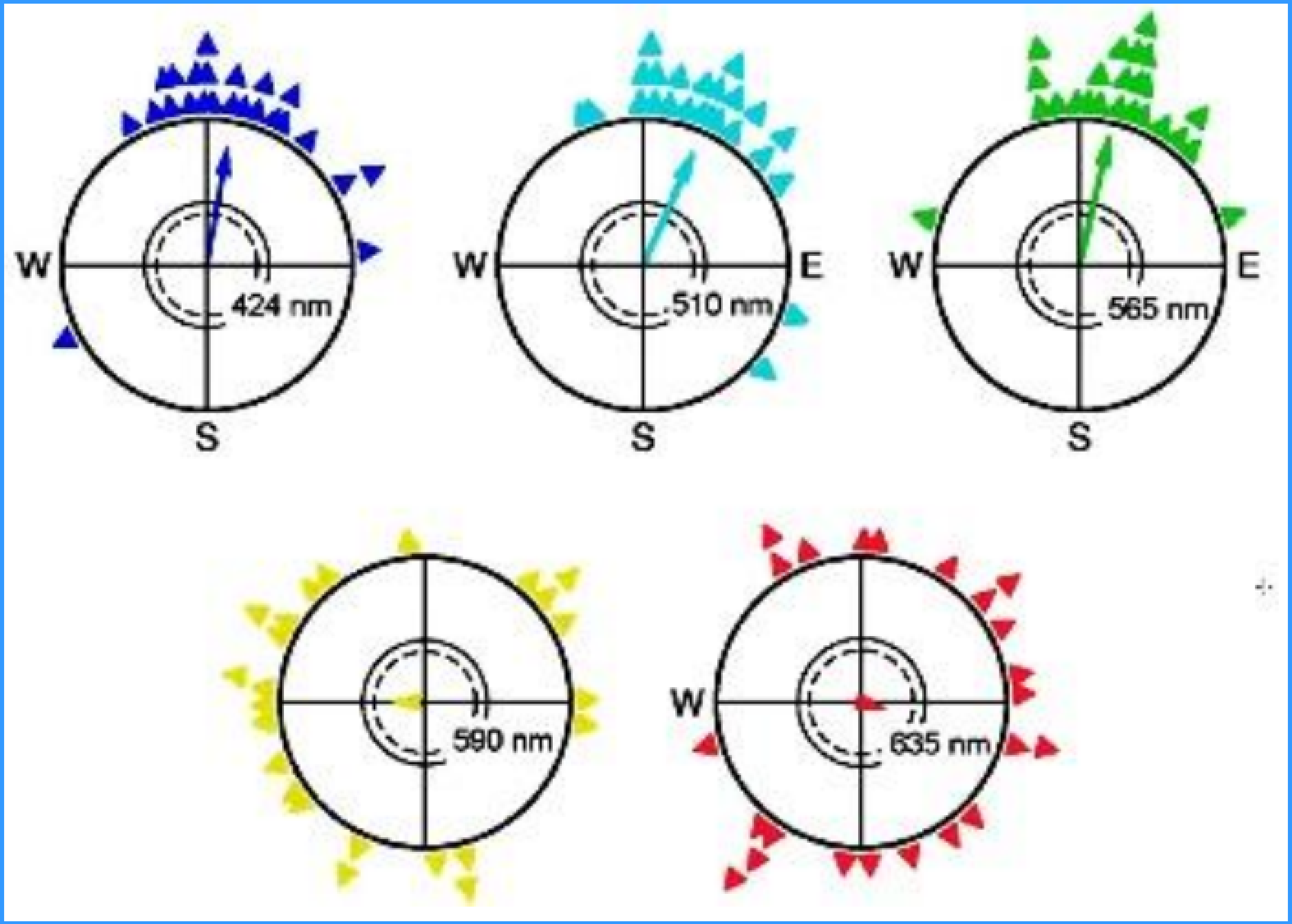
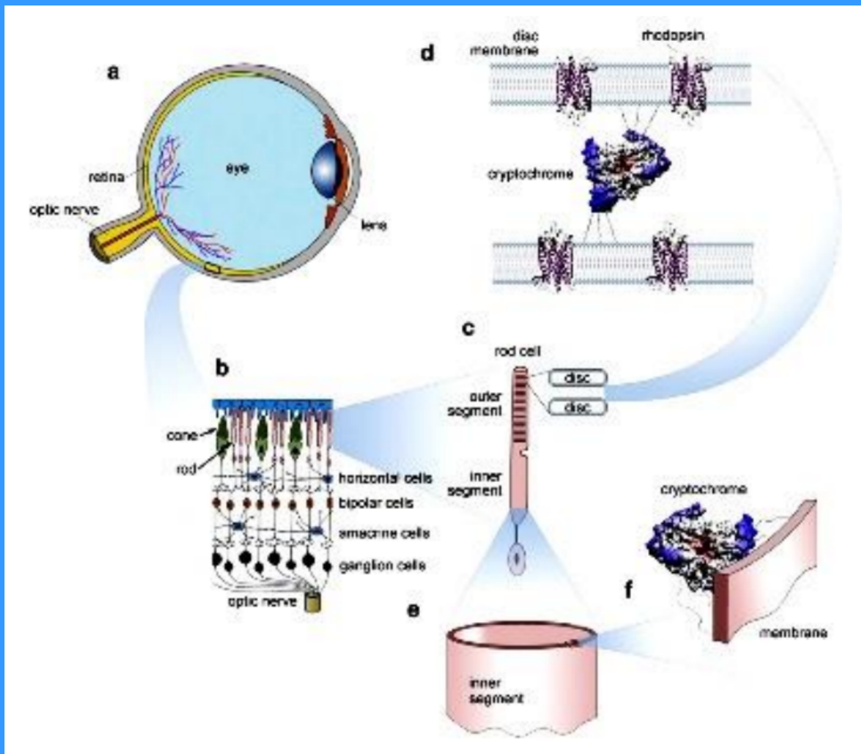


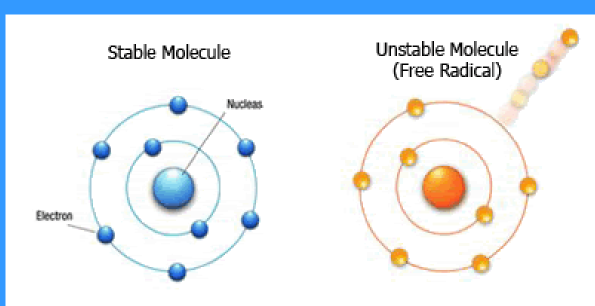
Illustration of the functional mode of avian inclination compass. A situation is shown for a bird migrating in spring in the Northern hemisphere in a northern direction. The bird in the left part of the graph is situated in the natural magnetic field of the Northern Hemisphere and flies towards the magnetic North. The bird in the right part of the graph is in the field with the inverted vertical component and flies towards the magnetic South.



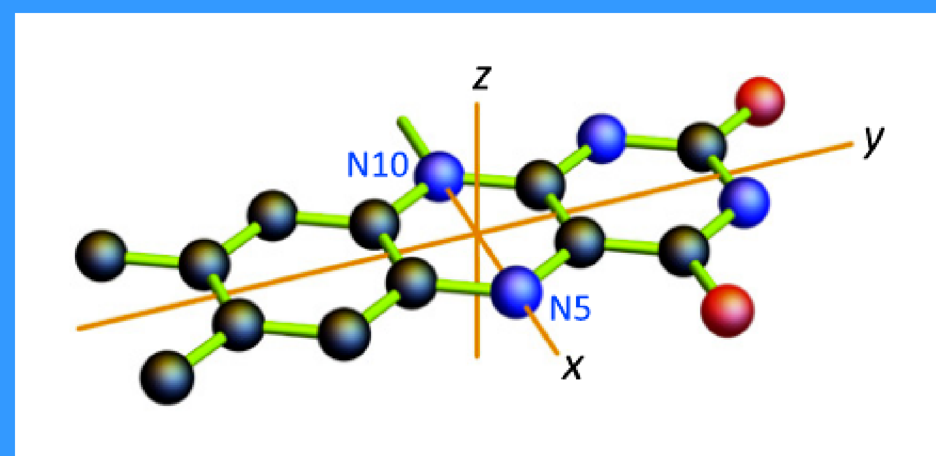
If the birds were tested under monochromatic yellow or red light, they were disoriented.

Migratory birds have a light-dependent magnetic compass, the mechanism of which is thought to involve radical pairs formed photochemically in cryptochrome proteins (photoactive pigment in the eye sensitive to blue light).





Free radicals



Tricyclic flavin ring system

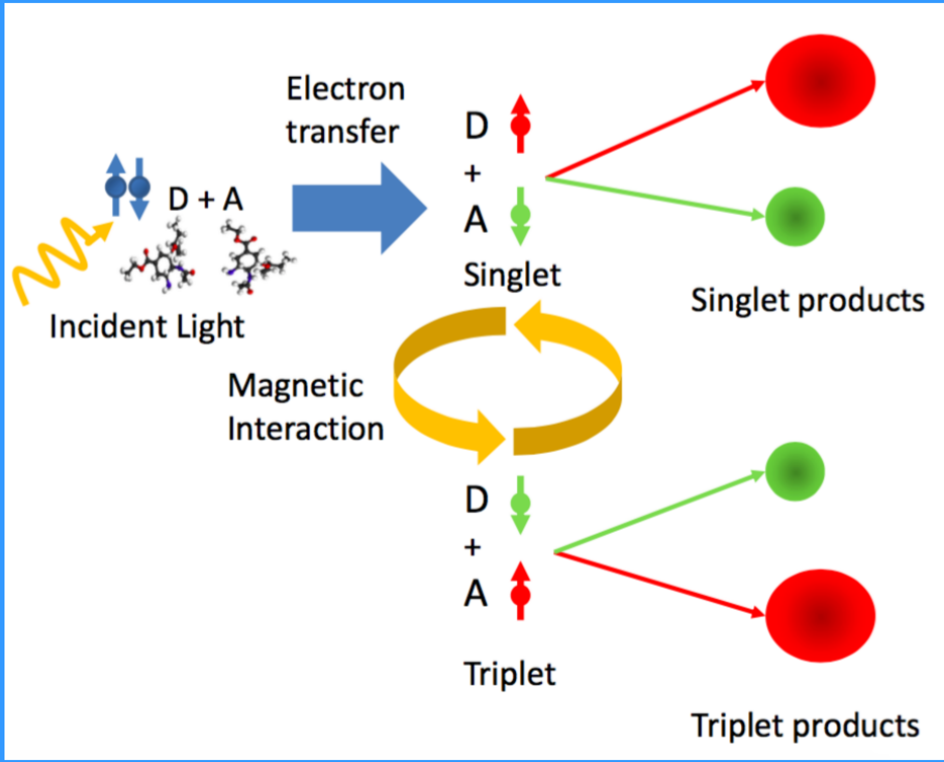
The light falls on the retina of the bird's eye, which contains photoreceptors of light, where the donor and acceptor are in a basic state. Absorption of a photon results in the transfer of a single electron from the donor to the acceptor, thereby forming a pair of radicals (its life time is several milliseconds).

Now the two spatially separated electrons interact with different local magnetic fields. While both electrons interact with earth magnetic field, one electron in addition interacts with a nuclear spin. This leads to an oscillation between singlet and triplet states. The time evolution of this oscillation depends on the angle with earth magnetic field ***B***. So, one can expect that the rate constants k_{SI} and k_{TR} related do the decay of both states into a singlet or triplet state have different values, leading to different relative concentration of product states.

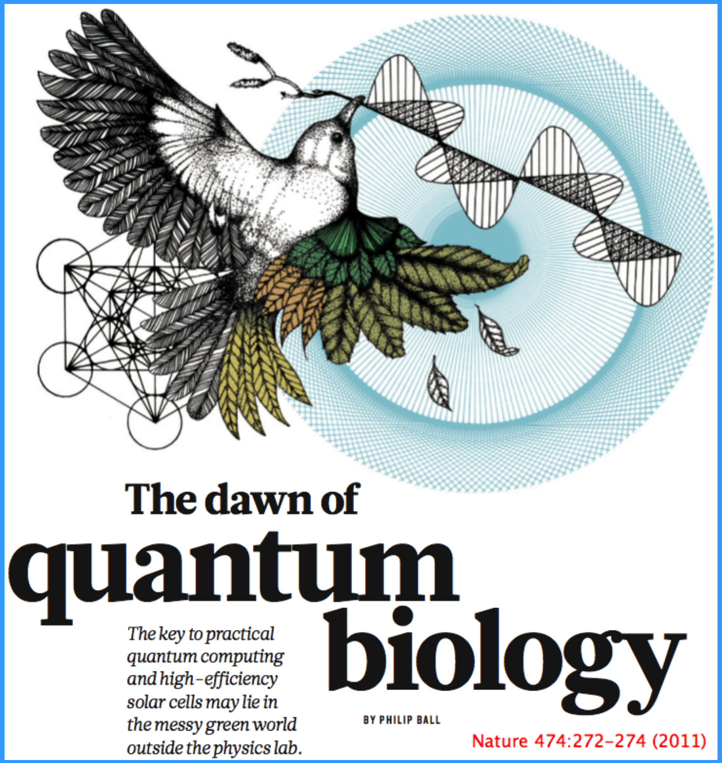
Magnetic interaction

$$H = \hat{I}\cdot\mathbf{A}\cdot\hat{S}_1 + \gamma\mathbf{B}\cdot(\hat{S}_1 + \hat{S}_2)$$

Hyperfine interaction

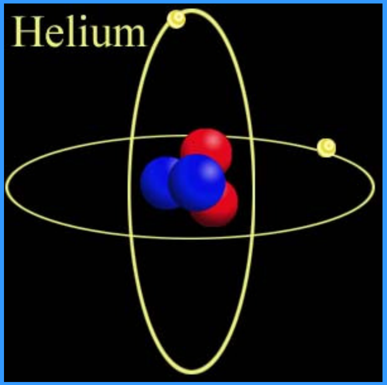


Generally, quantum phenomena have been observed at low temperatures in both microscopic and macroscopic systems. Presently, it seems that the effects can also occur at high temperatures if the systems are not in thermal equilibrium.



Decoherence due to contact with a hot environment typically restricts quantum phenomena to the low temperature limit, $k_B T/g\mu_B B \ll 1$ ($g\mu_B B$ is the single-particle Zeeman energy where μ_B is the Bohr magneton, k_B is the Boltzmann constant, and g is the Landé g-factor). But when a system is not in thermal equilibrium, the temperature no longer provides the relevant energy scale!

A system composed of multiple parts A, B, . . . is entangled if it is in a pure state ψ that cannot be described as a tensor product $\psi = \psi_A \otimes \psi_B \otimes \ldots$, where ψ_i denotes the wavefunction of part i.



The electron spin is a natural two-level system, where ↑, ↓ represent the eigenstates of the spin operator along some fixed direction. For instance, the ground state of a Helium atom is the spin singlet

$$\begin{aligned} |\uparrow\uparrow\rangle &= |\uparrow\rangle_A \otimes |\uparrow\rangle_B \\ |\uparrow\downarrow\rangle &= |\uparrow\rangle_A \otimes |\downarrow\rangle_B \\ |\downarrow\uparrow\rangle &= |\downarrow\rangle_A \otimes |\uparrow\rangle_B \\ |\downarrow\downarrow\rangle &= |\downarrow\rangle_A \otimes |\downarrow\rangle_B \end{aligned}$$

An orthogonal basis of product states, where the total spin is not well defined

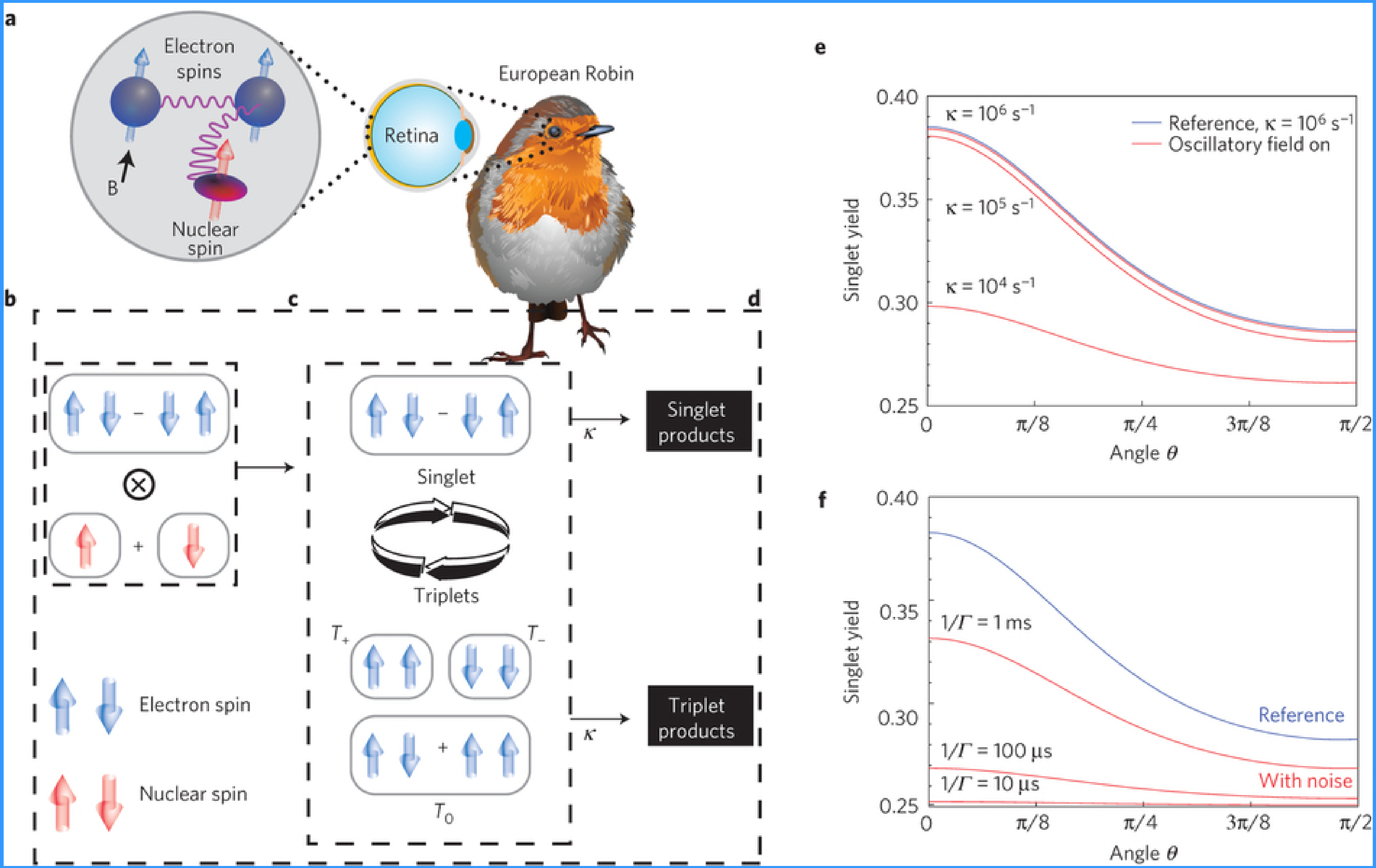
$$|1,\uparrow\rangle = |\uparrow\uparrow\rangle\,, \quad |1,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)\,, \quad |1,\downarrow\rangle = |\downarrow\downarrow\rangle$$

The spin 1 state is described by the symmetric (spin triplet) states

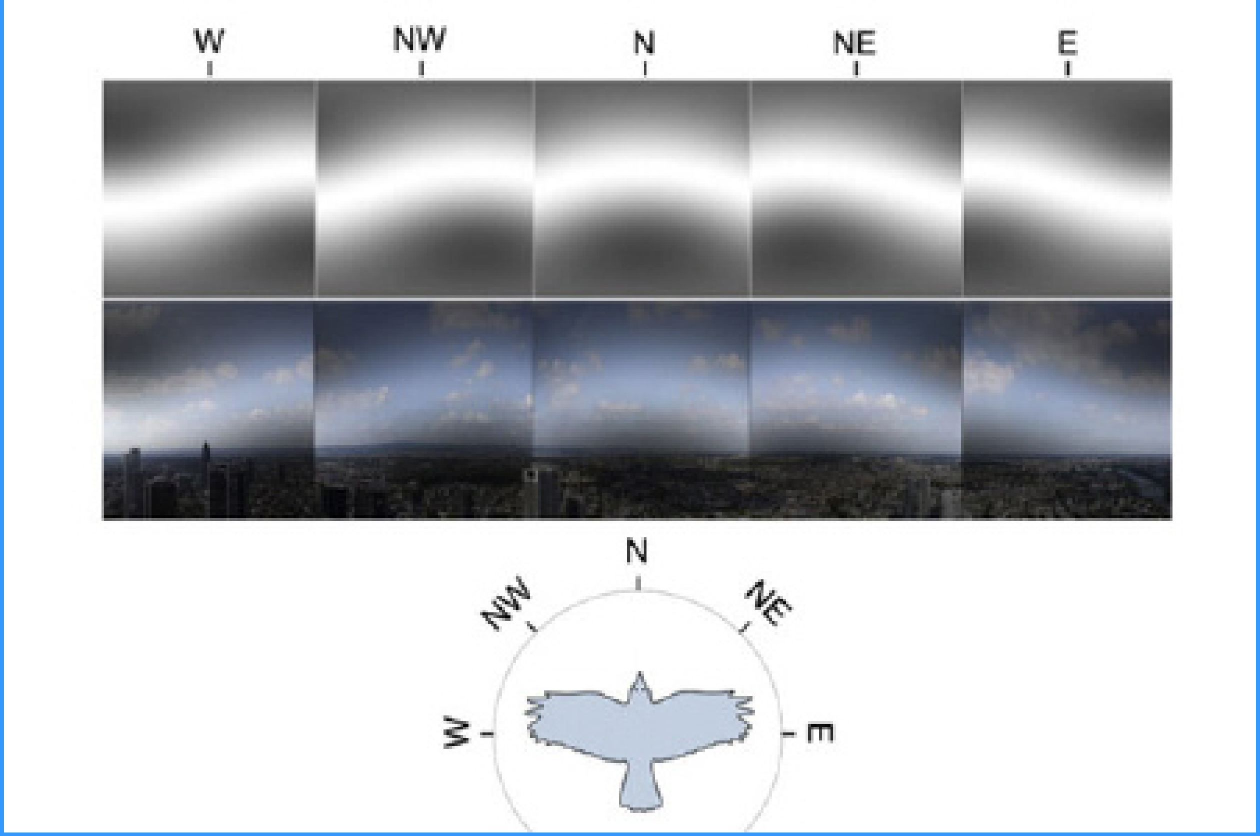
$$|0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

The spin 0 state is described by the antisymmetric (spin singlet) state

The ability to navigate depends on the light, and especially on the right eye and the left cerebral hemisphere. The bird's sensor is evidently activated by photons (blue or green light) entering. A crucial element is the presence of nuclear spins whose hyperfine interactions are the source of the magnetic anisotropy.



Different products of the biradical reaction may modulate the sensitivity of photoreceptors through a cascade of reactions. For instance, products of the triplet radical pair may inhibit transmission of visual information whereas singlet products may enhance it, or vice versa. As a result of these modulations, sensitivity of photoreceptors will vary between different parts of the retina, depending on the orientation of cryptochrome molecules relative to magnetic field vectors. As a result, a visual pattern of light and shade, appearing in the bird's field of view, provides orientation information.



It seems that the radical pair mechanism provides an instructive example of how the behaviour of macroscopic entities, like the European robin, may indeed remain connected, in an intriguing way, o quantum processes on the molecular level.

Markus Tiersch and Hans Briegel in

"Decoherence in the chemical compass: the role of decoherence for avian magnetoreception"