BIOLOGICAL EFFECTS OF VERY WEAK ELECTROMAGNETICAL FIELDS

Hans R. Zeller

Present Situation

- “Electrosensitive” persons are subject to acute health problems if close to a microwave basis station antenna.
- Public health authorities are concerned about long term health hazards of weak electromagnetic fields.
- The scientific literature is controversial and mostly of poor scientific quality. Successful replication experiments are very rare. Most results have been demonstrated to be spurious.
- The scientific evidence for negative health effects is very weak.
- Since hard scientific facts are missing, the discussion on potential health hazards is mostly ideological.
- Existing exposure limits are political and not based on scientific facts.

Present situation

- The only established interaction mechanism is heating due to absorption of field energy.
- In general the exposure is below the threshold for thermal effects.
- Non-thermal effects on biochemical reactions have been reported, but remain controversial.
- Proposed models for non-thermal effects are bizarre and outside established physics.

Scientific disciplines

- The interaction of electrical and magnetic fields with matter is the subject of electrochemistry, irreversible thermodynamics and physics.
- Biology deals with the consequences of such interactions.
- Scientific papers in the area are dominated by biologists, empirical sociologists, health officials, epidemiologists etc. Involvement of physicists or physical chemists has been missing.

Structure of the lectures

- Lecture 1
  - In search of a non-thermal mechanism:
    - The history of science teaches us that observations for which, even after long time, no causal mechanism is found, turn out to be spurious.
    - Systematic search for a causal mechanism based on fundamental laws of physics.
    - Introduction of a causal mechanism and discussion of its implications.
- Lecture 2
  - What is the experimental evidence of weak field effects in biological matter?
  - Are there negative effects on human health?

In search of a mechanism

Susceptibilities

$$\text{Response} = \chi \cdot \text{Stimulus}$$

$$j = \sigma \cdot E$$

Examples

$$\vec{D}_i = \varepsilon_{i,k} \cdot \varepsilon_0 \cdot \vec{E}_k$$

$$v = \mu \cdot E$$

The susceptibility χ relates two physical properties. The susceptibility may be a complex number, a tensor etc. It is constant and does not depend on the magnitude of the cause.

This is called **LINEAR RESPONSE**.

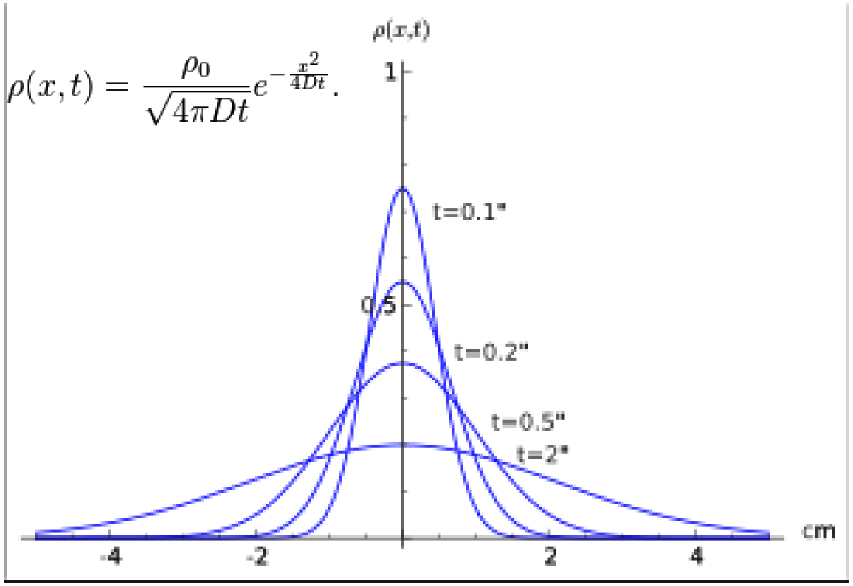
Thermal Fluctuations

Particles in a liquid or a gas perform a random motion. If ρ(x,t) is the densitiy Of particles at time t and location x, then we find:

$$\frac{\partial \rho}{\partial t} = D\frac{\partial^2 \rho}{\partial x^2},$$

D is the diffusion constant.

Time dependence of the density for a delta function of ρ(x,t) at t = 0.



Fluctuation- Dissipation Theorem

$v = \mu_{diss} E$

The mobility μ_{diss} is limited by the momentum dissipation of the particle when it moves under the action of an electrical field.

$D = \mu_{therm} k T$

k is the Boltzmann constant, T the absolute temperature and μ_{therm} the mobility due to thermal motion.

Einstein – Nernst - Smoluchowski

$$\mu_{therm} = \mu_{diss}$$

Kubo and others generalized the theorem. It applies, if the response is linear and if the system is near thermal equilibrium.

The theorem says that within linear response any response to a stimulus can be derived from thermal fluctuations. Within the validity of the Fluctuation – Dissipation Theorem any response to a stimulus can be derived from thermal fluctuations.

Example

Thermal fluctuation properties and suceptibilities can be mapped on each other.

Example: Thermal noise of a resistor.

$$R = \frac{\langle V^2 \rangle}{4 \cdot k \cdot T \cdot \Delta\upsilon}$$

$\langle V^2 \rangle$ is the mean square noise voltage, k is the Boltzmann constant and $\Delta\nu$ the bandwith. The fluctuation - dissipation theorem relates the fluctuation property $<V^2>$ to the susceptibility R.

The frequency dependent dielectric constant can be derived from the noise spectrum of a dielectric.

Limits of the Fluctuation – Dissipation Theorem

- The theorem holds only, if the system is close to thermodynamic equilibrium.
- Linear response as validity criterion:
  - Nonlinear susceptibilities are linearized by thermal fluctuations as long as the system is near equilibrium (example: p-n diode).
  - Near equilibrium means that the characteristic energy U of the interaction is $<<$ kT (approx. 30 meV).
  - Linear response implies that the criterion is fulfilled.
- The theorem does not apply if the response is nonlinear.
- Non-thermal interactions can only occur if $U \geq kT$.

→ Discuss U for different electromagnetic interactions.

Electrical Field Effects

- Ionic conductivity

The motion of an ion in a liquid is described by the Langevin equation:

$$\cancel{m \cdot \frac{d^2x(t)}{dt^2}} = -\gamma \cdot \frac{dx(t)}{dt} + q \cdot E(x,t) + f(t)$$

γ is a friction coefficient an f(t) represents the thermal fluctuations.

If E(t) is a step function, then the particle or ion will attain its equilibrium drift velocity after a characteristic time m/γ. For ions the second derivative inertial term can be neglected. The ion will reach its drift velocity instantly on a microwave time scale. This means that the ion motion is overdamped. Inertial terms in the equation which could lead to resonant energy build up are inexistent. The system is thus sufficiently close to thermal equilibrium for the Fluctuation - Dissipation Theorem to apply independent of field strength.

Electronic conductivity

High mobility electronic conductivity in organic crystals is based on extended π-states in aromatic molecules. Such systems do not exist in biological matter. In organic materials electronic conductivity is unimportant. If it occurs, then it is a hopping conductivity from one localized state to the next. Occasional reports on high mobility electronic conductivity in bacteria are in contradiction with elementary solid state physics and have never been satisfactorily replicated.

In hopping conductivity the maximum electron energy, neglecting scattering, is electrical field times hopping distance. With hopping distances less than 100 nm, no significant kinetic energy build up can occur at small fields.

Dipole Relaxation

Polar molecules in liquids and in some cases also in solids have rotational degrees of freedom. To rotate, they have to overcome a potential barrier. The rotation is thus thermally activated. As a consequence it exhibits no memory. The equation of motion thus has no mass term. In its simplest form the orientational polarisation is described by:

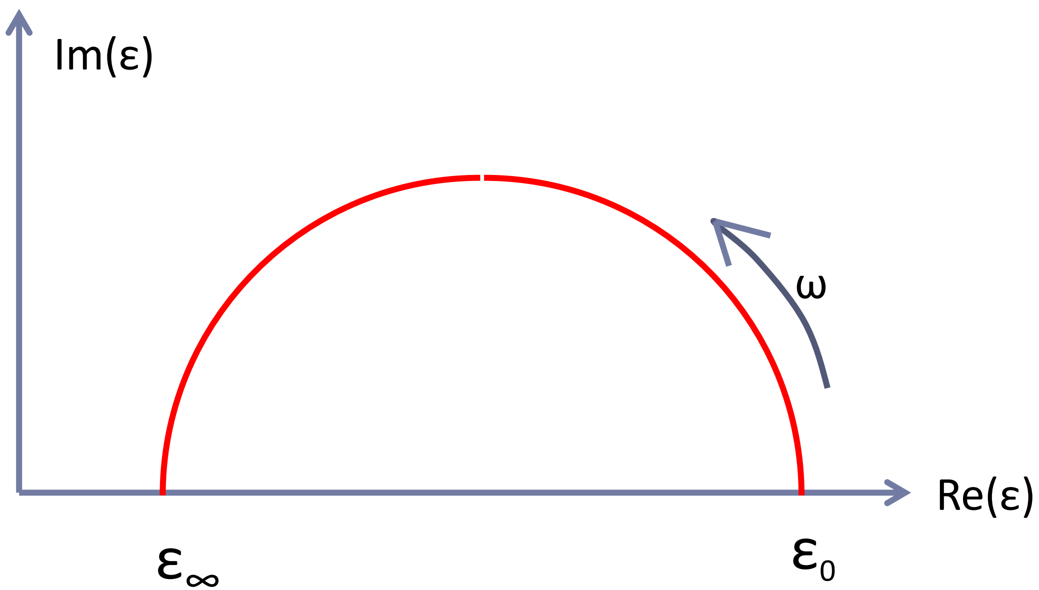
$$\frac{dP(t)}{dt} = -\frac{1}{\tau} \cdot P(t)$$

with the solution: $P(t) = P(0) \cdot \exp(-\frac{t}{\tau})$

A Laplace transform results in the equation for the dielectric function:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + i \cdot \omega \cdot t} = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + \omega^2 \cdot \tau^2} + i \cdot \frac{(\varepsilon_0 - \varepsilon_\infty) \cdot \omega \cdot \tau}{1 + \omega^2 \cdot \tau^2}$$

Frequency dependence of the dielectric constant



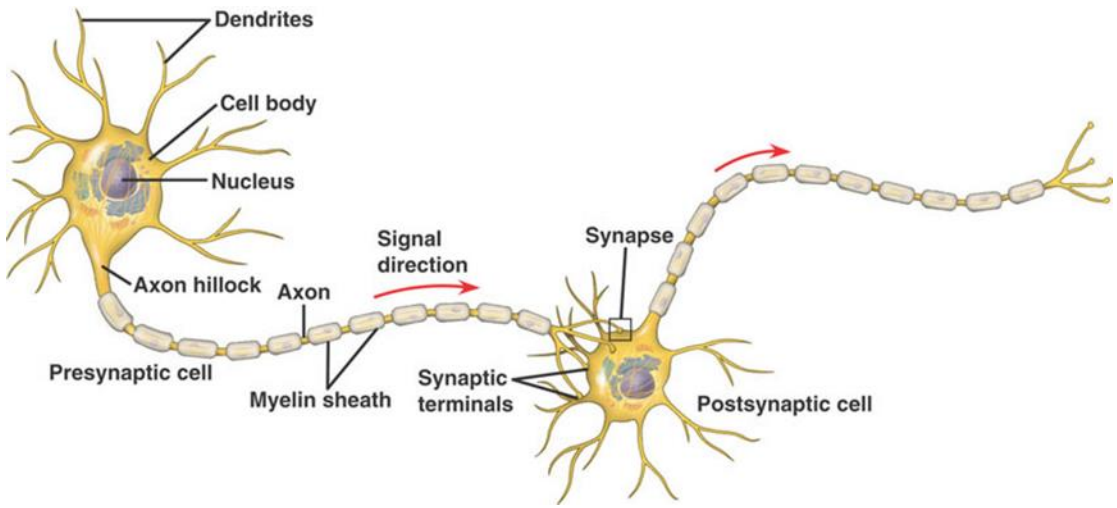
In most cases the situation is more complex. The semicircle is flattened and the curve does not cross the axis at a 90^0 angle. If different species contribute, then a superposition of circle segments is observed.

Biological Material contains different classes of molecules which show dielectric relaxation. The characteristic frequencies range from kHz to more than 10 GHz.

Conclusion

- The Fluctuation – Dissipation Theorem is applicable. There are no non-thermal effects of weak electrical fields on a molecular level. The only effect is heating.
- The biologists objections:
  - Biological materials are inhomogeneous. They contain discontinuities such as membranes.
  - Modelling the response of an inhomogeneous biological system to electrical fields if hopeless.
- The physicists response:
  - The complexity of the systems makes it simple to model the worst case.

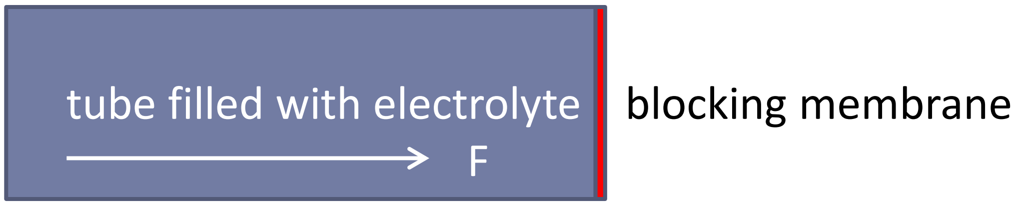
Neurons



Neuron activity is controlled by membrane potentials. Several types of ion channel pumps control potential gradients.

Realistic modelling of the effect of electromagnetic fields on membrane potentials is impossible.

Heterogeneous biological materials



- The worst case for nonlinear polarization effects:
  - The inhomogeneity is a discrete step discontinuity (membrane).
  - The membrane is electrically blocking
  - The electrical field is perpendicular to the membrane
  - Depolarization effects are ignored.
- This maximizes the charge build-up at the interface during a half wave.

The charge layer at the membrane

We consider a field of the form:

$$F(t) = F_0 \cdot \exp(i \cdot \omega \cdot t)$$

This induces at the interface an oscillating charge with amplitude: (σ is the conductivity of the electrolyte).

$$\Delta Q = \sigma \cdot \frac{F_0}{\omega}$$

The thickness x of the interfacial charge layer can be estimated from elementary electrochemistry.

$$x = \sqrt{\frac{\varepsilon \cdot \varepsilon_0 \cdot k \cdot T}{2 \cdot N \cdot e^2 \cdot I}}$$

N = 6.022 10^{23} Mol^{-1} is Avogadros Number and I the ionic strenght of the electrolyte. For a physiological NaCl solution I = 0.154 Mol/kg. With ε = 80 we find: x = 0.62 nm.

Effect on ion concentration at interface

Change in electrochemical potential at the interface:

$$\Delta\mu = \Delta Q \cdot \frac{x}{\varepsilon \cdot \varepsilon_0} = \frac{\sigma \cdot x}{\omega \cdot \varepsilon \cdot \varepsilon_0} \cdot F_0$$

This leads to change in the ion concentration at the interface of:

$$\Delta C = C_0 \cdot (\exp(\frac{\Delta\mu \cdot e \cdot z}{k \cdot T}) - 1) = C_0 \cdot (\exp(\frac{\sigma \cdot x \cdot e \cdot z \cdot F_0}{\omega \cdot \varepsilon \cdot \varepsilon_0 \cdot k \cdot T}) - 1)$$

C_0 is the volume ion concentration, and z the valency (Na^+, Cl^- z = 1, Ca^{++} z= 2). σ is the electrical conductivity.

If the exponent is > 1then the nonlinearity causes a rectification, similar to the rectification in a p-n diode.

Critical field for non-thermal effects

$$F_{crit} = \left(\frac{\varepsilon \cdot \varepsilon_0 \cdot k \cdot T}{z \cdot e \cdot \sigma \cdot x}\right) \cdot \omega$$

For $z = 1$, $\sigma = 1$ S/m (an upper bound for the conductivity in biological matter), $\varepsilon = 80$, $x = 1$ nm, we obtain:

F_{crit}(V/m) = 0.0177 ω (sec^{-1}).

For f = 100 Hz the critical field for the onset of non-thermal effects is above 11 V/m. For 1 MHz it would be above111 kV/m. Note: F_{crit} is not the external field, it is the field inside the body.

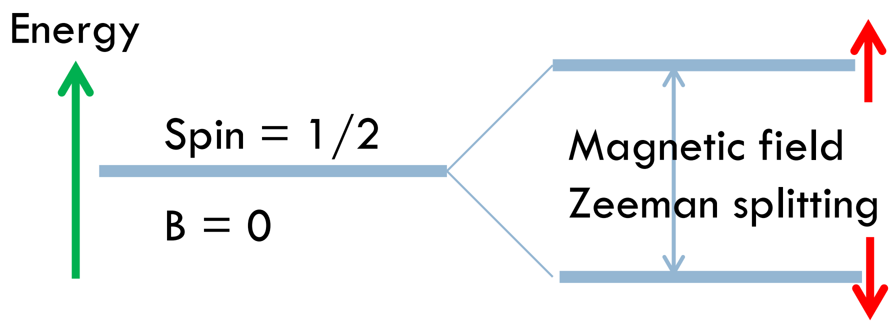
This is the theory of the electrical shock

Magnetic Fields - Diamagnetics

- Biological matter is almost completely diamagnetic.
- The diamagnetic susceptibility is anisotropic. Very strong magnetic fields cause mechanical forces and in collectively aligned molecules also torques.
- Dielectric magneto-mechanical effects are insignificant below B = 1 Tesla (10’000 Gauss).

Para- and Ferromagnetism

- Free radicals are paramagnetic. Some molecules containing transition metal ions also exhibit paramagnetism.
  The Zeeman splitting is small compared to kT even at B = 10 Tesla (100'000 Gauss).

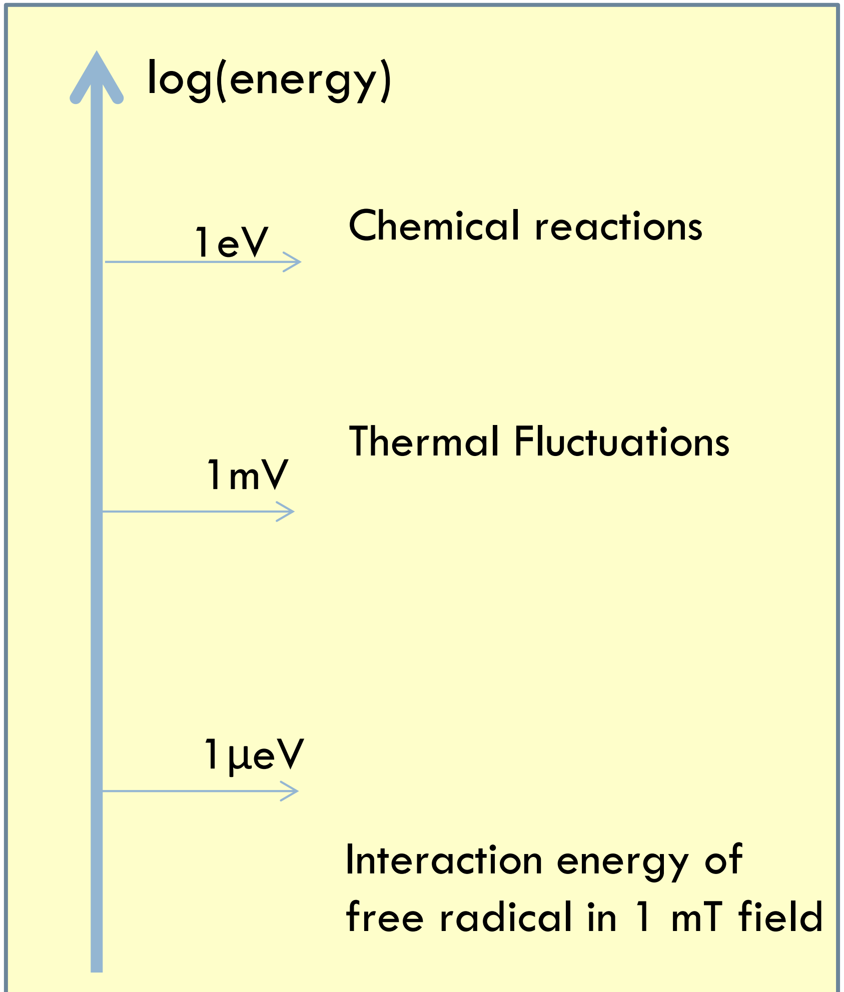


- Some animals form ferromagnetic particles in their tissues. Such particles can exhibit magneto-mechanical effects at static and quasistatic fields, but not at high frequencies. The particles are probably used for magnetic direction sensing.
- Magneto-mechanical effects cannot account for reported chemical effects of microwave radiation.

Conclusion

- The only non-thermal effect of weak electrical fields is the electrical shock at very low frequencies.
- Diamagnetic materials, paramagnetic ions and magnetic particles are incapable to cause non-thermal effects at weak magnetic fields.
- Weak electromagnetic fields are not capable to induce any dissipative processes except heating.

The Killer Argument



Consequence:

- Models of the type:
  response = susceptibilty x stimulus
  are out.
- Models based on energy dissipation are out.

- Find model which explains chemical effects of extremely weak fields.
- Find model in which the energy scale on the left is meaningless.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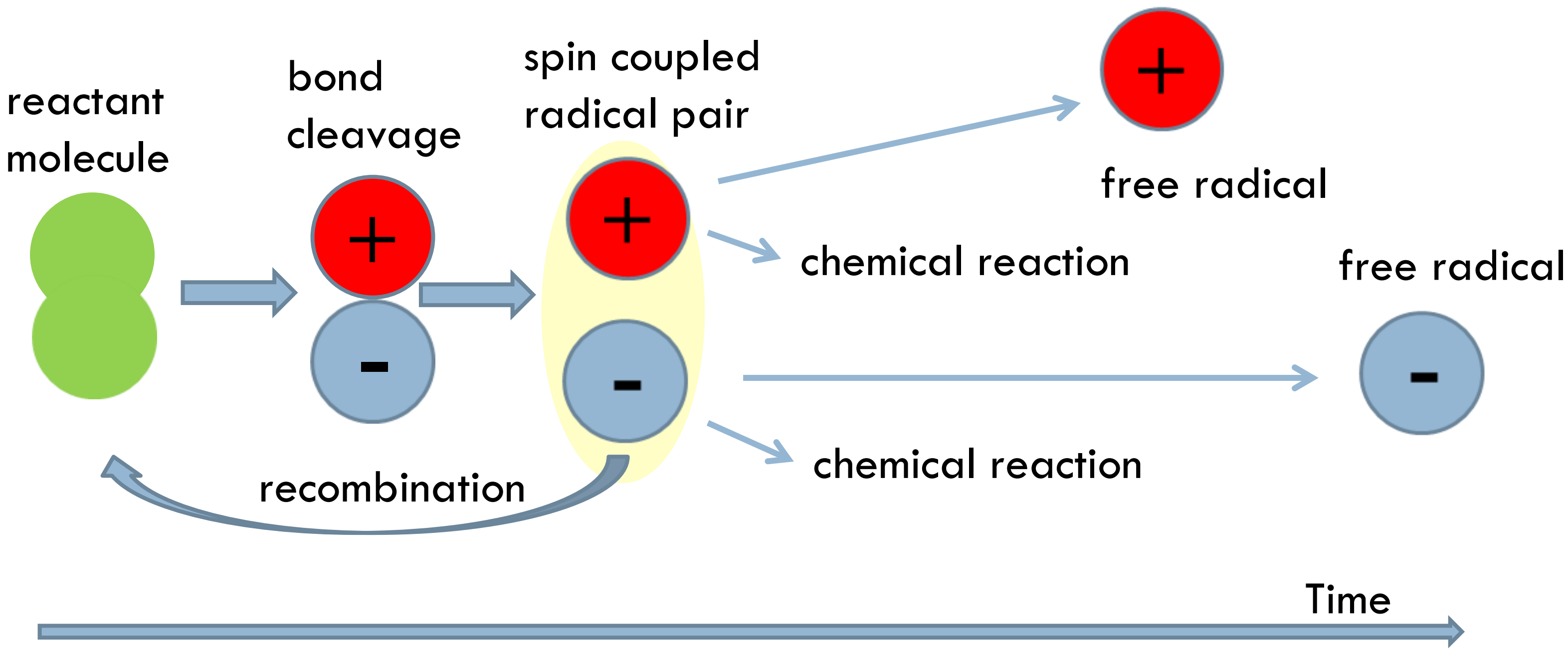
Symmetry breaking

- The electrical field and its effects are invariant under time reversal.
- The magnetic field and its effects are not invariant under time reversal.
  - Consequence:
    The spin states are no longer exact eigenstates in the presence of a magnetic field. The magnetic field mixes spin states.

Spin coupled radical pairs



An electron has a magnetic moment and parallel to it an angular momentum (spin S). Two electrons form either a singlet (S = 0, spins antiparallel ↑↓) or a triplet (S = 1, spins parallel ↑↑).

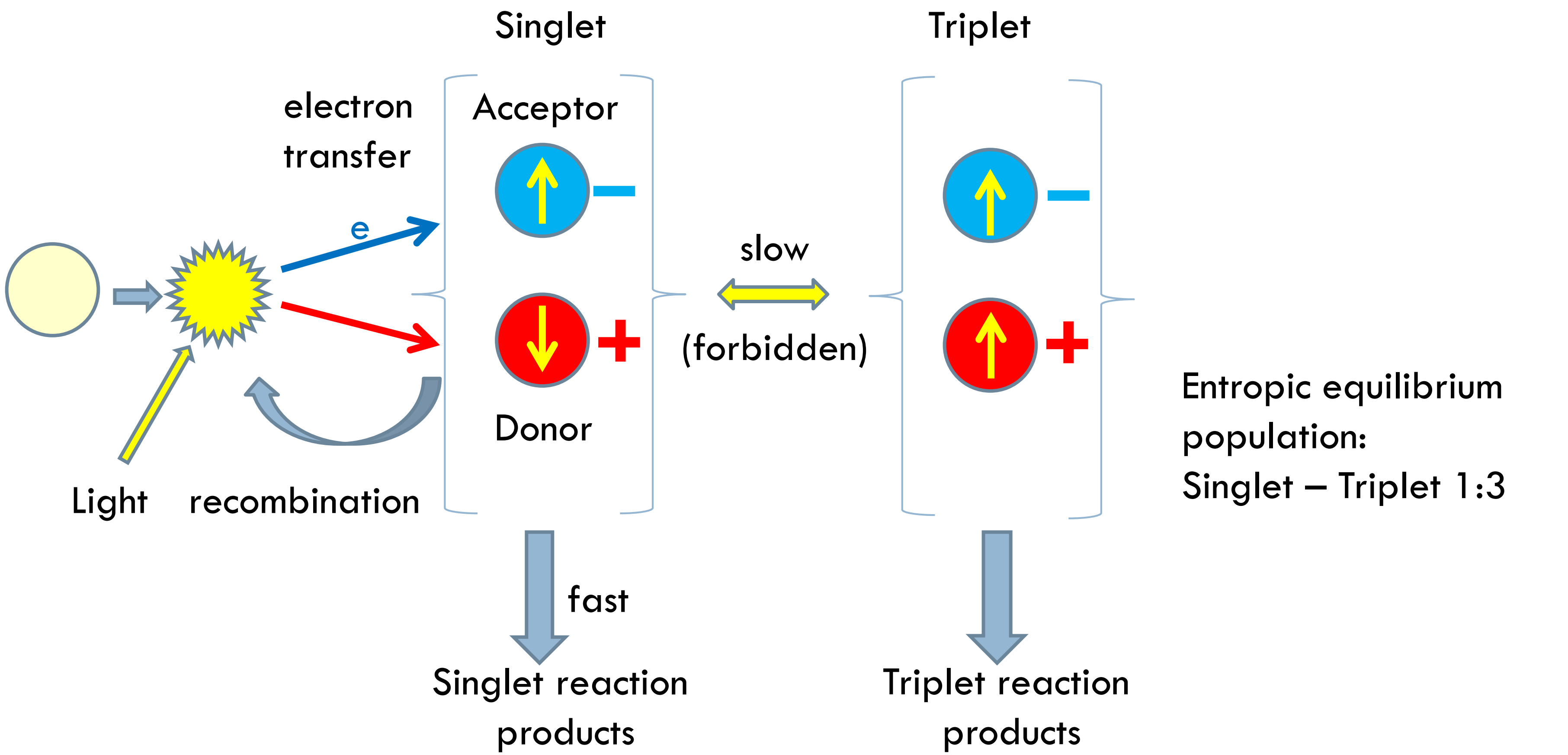
Spin coupled radical pairs

- Spin states are long lived on the timescale of a chemical reaction because of spin conservation.

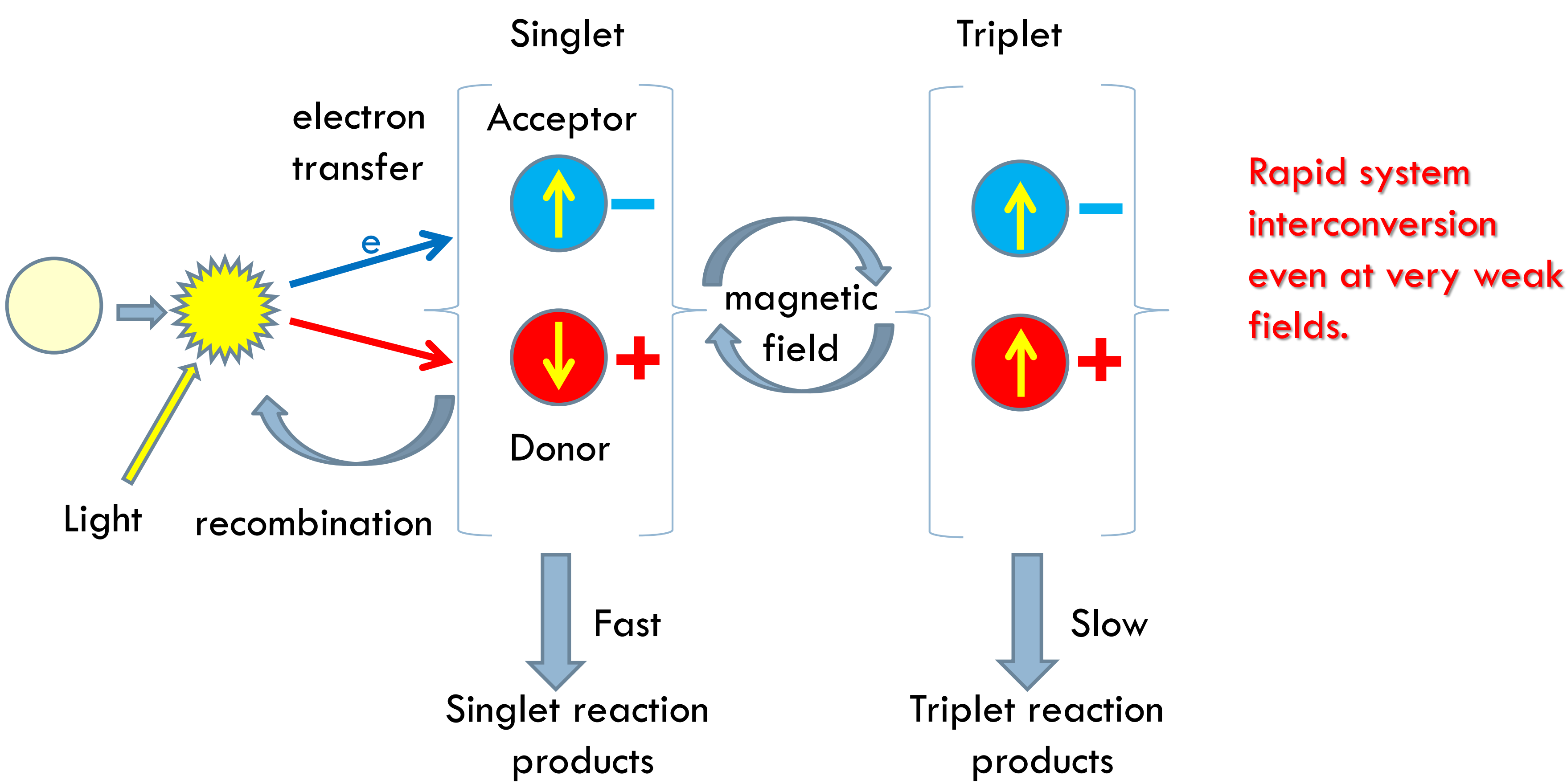
$$\sum_{i} \vec{S}_{i}^{\text{reactants}} = \sum_{j} \vec{S}_{j}^{\text{products}}$$

- Spin states affect chemical reaction kinetics.
  - Excited singlet state (reactant) → singlet product: fast (less than 1 µsec).
  - Excited triplet state (reactant) → singlet product: slow (several µsec or more).

Radical pair (B = 0, hyperfine coupling = 0)



Radical pair in magnetic field



Hyperfine Coupling

- Many nuclei in biological molecules have a nuclear spin (examples ^{1}H, ^{14}N, ^{57}Fe (2.1%), ^{31}P, and ^{25}Mg (10%).
- The magnetic moment of the nuclear spin induces a magnetic field which interacts with the electron spin.
- For historic reasons this is called hyperfine coupling.

Spin coupled radical pair

Spin Hamiltonian (quasi-static magnetic field B):

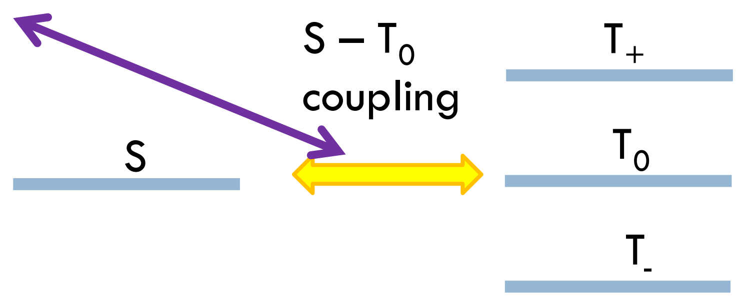
$$H = \mu_B \cdot (g_1 \cdot S_1 \cdot B + g_2 \cdot S_2 \cdot B) + \sum_i a_{i1} \cdot I_{i1} \cdot S_1 + \sum_i a_{i2} \cdot I_{i2} \cdot S_{21}$$

a_{i1} describes the hyperfine coupling (HFC) of nucleus i with nuclear spin I to electron spin S_1.

Example:
Only radical 1 has a nucleus with nuclear spin I = ½. The magnetic field B is zero. The off-diagonal matrix element, coupling the singlet state S to the triplet state T_0, becomes:

$$\langle T_0 | H | S \rangle = \frac{1}{2} \cdot a \cdot m$$

m is the nuclear spin quantum number.



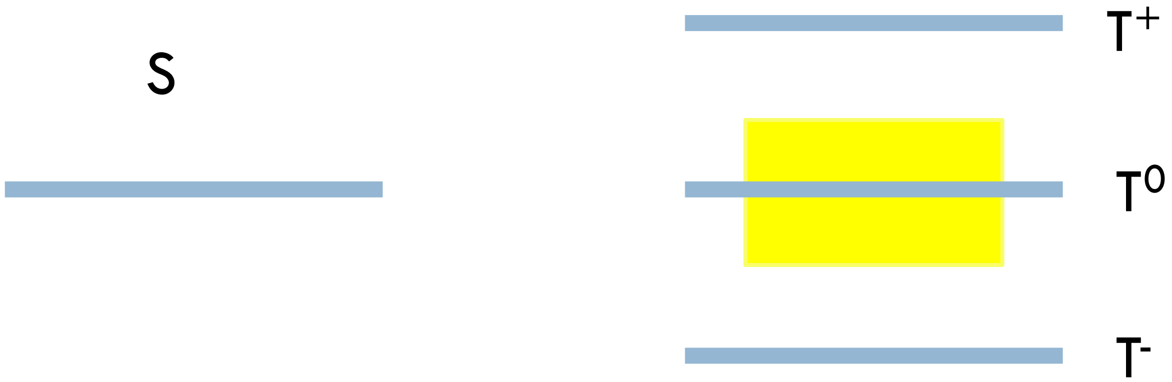
Singlet-Triplet entanglement in magnetic field

A magnetic field causes coherent oscillations between singlet and triplet state. The oscillation frequency is given by the Zeeman splitting. For an electron spin (g = 2.00) the frequency is of the order of

$$f \approx 28\ \mathrm{MHz/mTesla}\ (2.8\ \mathrm{MHz/Gauss})$$

Even at the geomagnetic field of 0.05 mT the oscillation frequency is in the range of excited state life times.

Singlet-Triplet entanglement in magnetic field



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Hyperfine Coupling

- The oscillations occur even without an external magnetic field due to the Hyperfine Coupling (HFC).
- HFC is the interaction between the electron spin and the magnetic field caused by a nuclear spin on the same molecule.
- Examples of nuclei in biological matter with spin are ^{1}H, ^{14}N, ^{57}Fe (2.1%), ^{31}P, and ^{25}Mg (10%).
- HFC fields are in the range of 0 – 5 mT resulting in oscillation frequencies between 0 and 150 MHz.
- Chemical effects of (quasi) static external magnetic fields set in, when the field is of the order of the HFC field.

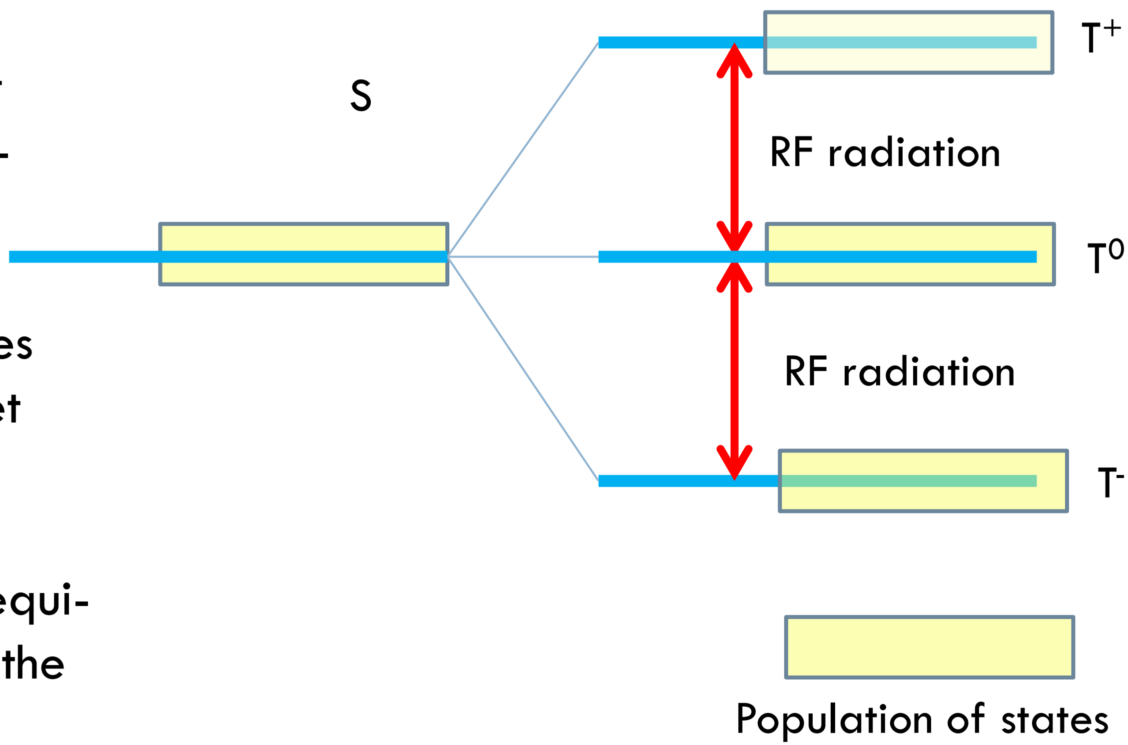
Competing kinetics

- Spin kinetics (singlet – triplet oscillations) (1 nsec – 10 µsec)
- Chemical reaction kinetics (singlet: ≤1µsec, triplet substantially longer).
- Diffusion kinetics (spin correlation is lost by diffusion) (depends on viscosity, typically 1 -10 µsec range)
- Thermal relaxation: Equilibrium corresponds to equal population of each spin state (S = ¼, T = ¾), typically 1 - 10 µsec.

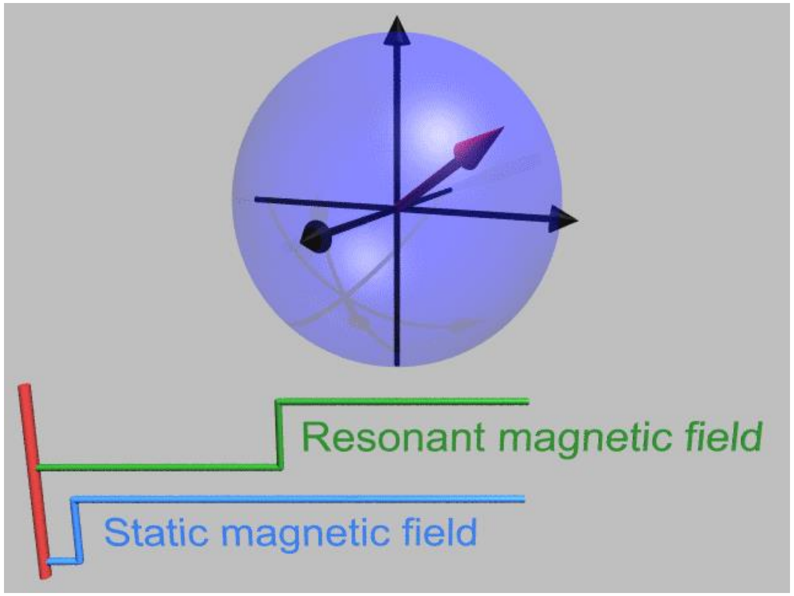
Effect of weak RF Fields

Irradiation with a resonant RF field polarized perpendicular to the static field leads to transitions within the triplet states. This causes an average singlet – triplet population ratio of 1 : 3.

The ratio 1 : 3 is also the equilibrium population ratio in the absence of any fields.



Precession in the rotating frame



To understand the action of the RF field it is best to do this in a frame rotating with the precession frequency of the static magnetic field B_0.

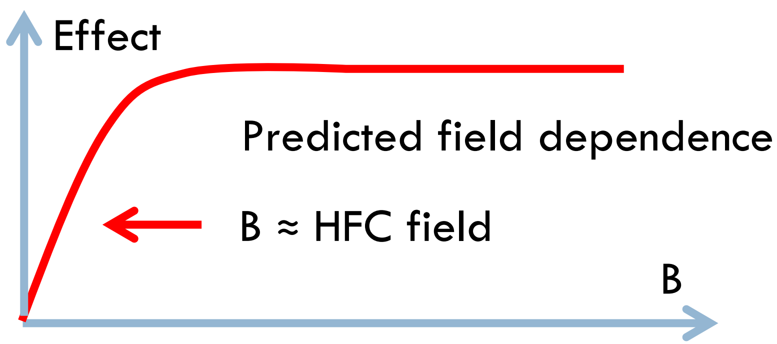
In this reference system the spin magnetization rotates around the oscillatory field B_1.

Competitive kinetic effects

- Spin kinetics
  - Singlet - triplet exchange kinetics caused by hyperfine coupling, spin-orbit interaction, exchange interaction and external (quasi) static and HF magnetic fields.
- Chemical reaction kinetics
  - Donor – acceptor recombination
  - Chemical reactions into stable products
- Diffusion kinetics
  - Spin coupling is lost due to distance increase. Transition into individual free radicals or other species.
- Thermalization
  - The thermal equilibrium populations is ¼ (Singlet), ¾ (Triplet).

Threshold magnetic field for chemical effects

- Spin kinetics has to be faster than chemical and diffusion kinetics. A characteristic time for chemical reactions of 1 μsec corresponds to a field of 6 nT.
- Diffusion kinetics is most likely unimportant in most biological systems.
- External quasistatic fields have to be at least of the order of the other S - T interchange mechanisms. Hyperfine coupling (HFC) fields range from 100 nT to a few mT.
- HF fields have to be in resonance.



Single point measurements without knowing the HFC strength and the reaction kinetics are of limited significance.

Threshold field for chemical effects

- The characteristic time for reaching the thermal equilibrium population ¼ (singlet), ¾ (triplet) in the absence of any external field and any hyperfine interaction is given by the longitudinal spin – lattice relaxation time T_1. T_1 is in the range a few μsec.
- RF fields can only have a chemical effect if they are resonant and of sufficient strength to induce a precession cycle in the rotating frame within T_1. For $g = 2$ and $T_1 = 6$ μsec this results in 1 nT.
- Intermediate products in a chemical reaction have typically a lifetime of < 1 μsec. This results in a higher threshold field of > 6 nT.

Electrical Threshold Field

- The relation between magnetic and electrical field in an electromagnetic wave is given by (c = velocity of light)
  $$B = \frac{1}{c} \cdot E$$
- This results in B(nT) = 3.3·E (V/m).
- A threshold field of 6 nT corresponds to 1.8 V/m. The threshold applies for frequencies in resonance with S – T interconversion.

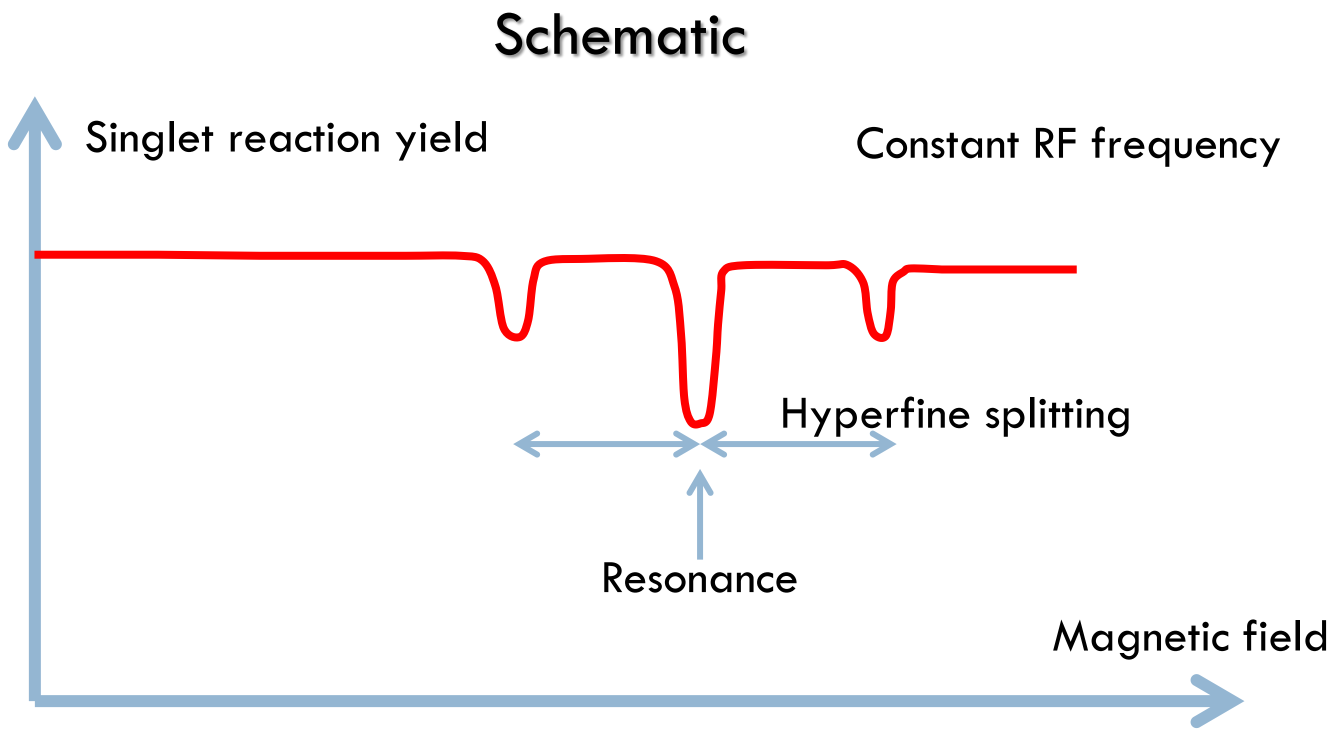
Experimental evidence of biological effects

- Experimental proof of spin-chemical effects in non-biological systems is uncontested. The relevant experiments date back more than 50 years.
- Experimental evidence of spin-chemical effects in biological systems is weak and controversial, even outside health relevant systems.
- In health relevant experiments there is no interaction between biologists and physicists.

How to exclude artefacts

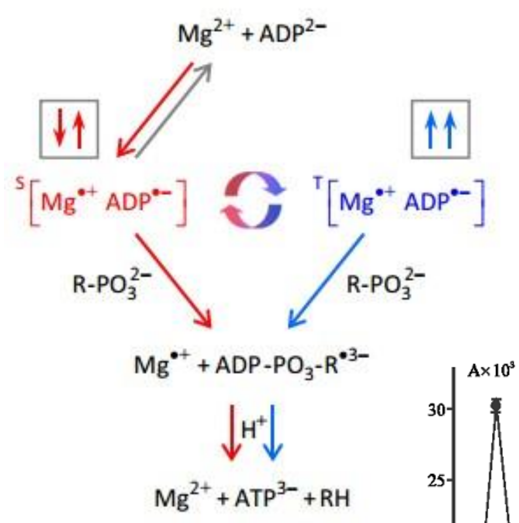
- **Very weak:** Experimental point reported by single group. No plausible model, no cause – effect relation.
- **Weak:** As above, but effect replicated by independent group.
- **Strong:** As above, but with cause – effect relation and plausible model
- **Convincing:** As above, but with independently confirmed model prediction.

Reaction yield detected electron spin resonance



Well established experimental technique. Effect on yield is consistent with standard ESR experiments, but rather unspectacular.

Hyperfine Coupling: Magnetic Isotope Effect



Enzymatic synthesis of ATP (Adenosine Triphosphate) from ADP (Adenosine Diphosphate):

In the absence of a Hyperfine Coupling (Mg isotope with spin zero) the back reaction reduces the yield. If the magnetic isotope $^{25}Mg^{++}$ is used, the back reaction is suppressed, the reaction yield increases. Similar effects have been found for the magnetic isotope $^{67}Zn^{++}$.

Zinc-Related Magnetic Isotope Effect in the Enzymatic ATP Synthesis: A Medicinal Potential of the Nuclear Spin Selectivity Phenomena, Anatoly L. Buchachenko, Vladimir P. Chekhonin, Alexey P. Orlov and Dimitry A. Kuznetsov, Int. J. Molecular Medicine and Advanced Sciences 6 (3): 34-37 (2010)

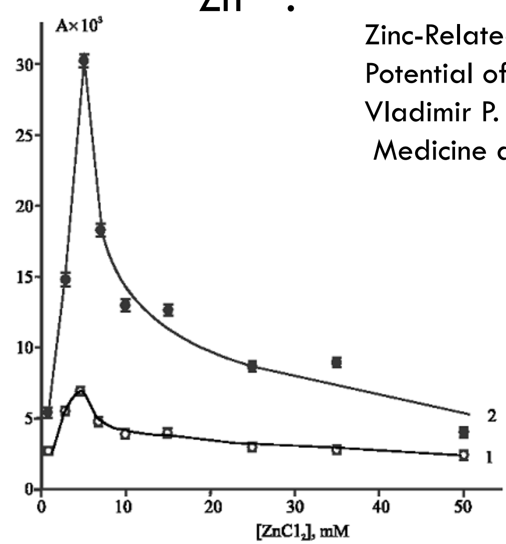


Fig. 1: The yield of ATP produced by CK as a function of $^{64}ZnCl_2$ (1) and $^{67}ZnCl_2$ (2) concentration

A replication study found no isotope effect at all.

www.pnas.org/content/109/5/1437.full.pdf

Stationary or quasistationary magnetic fields: Magnetic malaria treatment.

Lai et al. discovered that the growth of malaria parasites is suppressed by weak 5 Hz magnetic fields. This result was independently qualitatively confirmed by other groups. Surprisingly the suppression effect is **independent on field strength** in the range 0.68 – 6.8 mT. The suppression effect is too weak to be of clinical interest.

The parasite decomposes hemoglobin into globin which is digested and heme which is toxic. Detoxification occurs by removing the heme by forming hemozoin microcrystals inside the parasite.

The model proposed by the authors assumes that the hemozoin crystals are ferromagnetic, that they oscillate in the magnetic field and that the oscillation damages cell membranes.

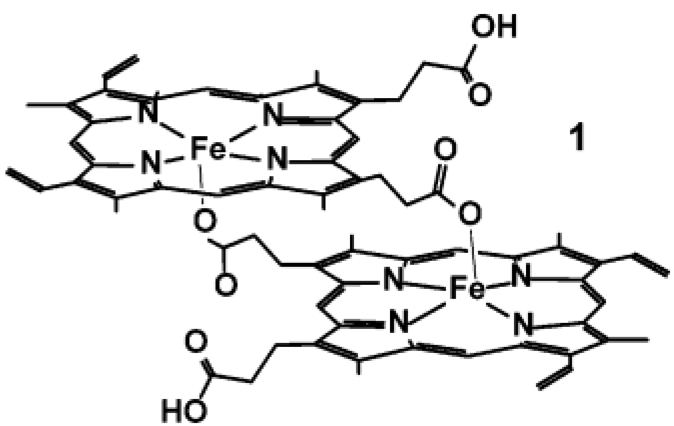
[6] Lai, Henry C; Jean Feagin, Ceon Ramin, and Michelle A Wurscher "Magnetic Fields and Malaria" Kluers Acedemic Publishers, 1999

http://blog.frequencyfoundation.com/2009/08/malaria-machine.html

Models for parasite suppression

The model is pure nonsense:

- Hemozoin is not ferromagnetic, but weakly paramagnetic.
- The magnetically induced vibration is small compared to Brownian motion.
- The “oscillation” of a microcrystal in water is equivalent to the “oscillation” of a macroscopic particle in extremely viscous honey.
- The magnetic energy scales as B^2. Increasing the field would lead to a large increase of the suppression effect. The effect is field independent.



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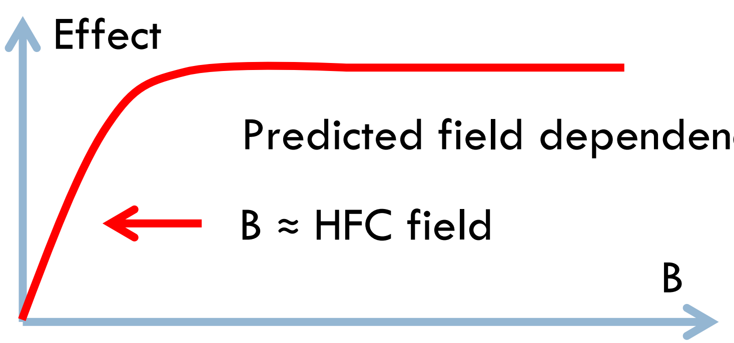
Hemozoin forms dimers. The Fe^{3+} ions are in the high spin $S = 5/2$ state → **Spin coupled radical pair.**



Andrzej Sienkiewicz, J. Krzystek, Bertrand Vileno, Guillaume Chatain, Aaron J. Kosar, D. Scott Bohle and Laszlo Forro, J. AM. CHEM. SOC. 2006, 128, 4534-4535.

Chemical magnetoreception in birds

- Migratory birds have the extraordinary ability to sense the Earth's magnetic field. There is convincing evidence that they use a spin-chemistry effect.
  - Direction sensing works only in blue, green and yellow light, but not with red light (< 565 nm wavelength)and in the dark.
  - The birds do not sense the field direction, but the field inclination.
  - Microwave radiation affects the sensing.
  - Changing the static magnetic field suppresses the sensing ability, but the birds recover it after some time.

Model

- Cryptochrome photoreceptor in the eye forms radical pairs after excitation with short wave length light.
- The sensing molecules are aligned. Anisotropic HFC leads to a direction dependent spin-chemical effect which is detected by the birds.
- This is not a compass. The effect is independent of the sign of the field. Because the bird knows up and down, it can sense the field inclination.
- Photosynthetic reaction center proteins where light absorption leads to radical pair formation by subsequent charge transfer are the best documented examples of magnetic field effects in biological systems.

Christopher T. Rodgers and P. J. Hore, PNAS 106, 356-360 (2009)

Effect of RF Fields

- Linearly polarized RF fields as weak as 5 nT (1.5 V/m in air) disturb the orientation capability of the birds if they match a S – T interconversion frequency (Zeeman splitting 1.4 MHz, hyperfine splitting 7 MHz), but only if they form an angle with the Earth magnetic field.
- The same RF field aligned with the Earth magnetic field has no effect.
- A broad band RF signal (0.1 – 10 MHz) at 85 nT (26 V/m in air) also disturbs the orientation capability of the birds.

Potential Health Effects

- Immediate effects on “electrosensitive” persons in the vicinity of a microwave antenna or an ac transmission line.
- Health related results obtained with cell culture experiments.

Immediate effects: Electrosensitivity

- The University of Essex has carried out a study which lasted over 3 years. Participants were 44 persons who complained about serious symptoms when exposed to microwave radiation and 114 persons who had no symptoms
- Both groups were exposed to microwave radiation for 50 min per day. The “electrosensitive” group had symptoms such as nausea, headache and flue-like symptoms. 12 persons had to terminate the experiment because the symptoms were very severe. The “insensitive” group reported no symptoms.
- Only 50% of the participants were exposed to microwave radiation. There was no difference in symptoms between the exposed group and the placebo group.

The Nocebo Effect

Nov. 5, 2012 in a mail distribution center in Switzerland: A white powder creeps out of two letters.

Immediately most employees become seriously ill. 37 have to be hospitalized. The fear is that the powder is causing Anthrax.

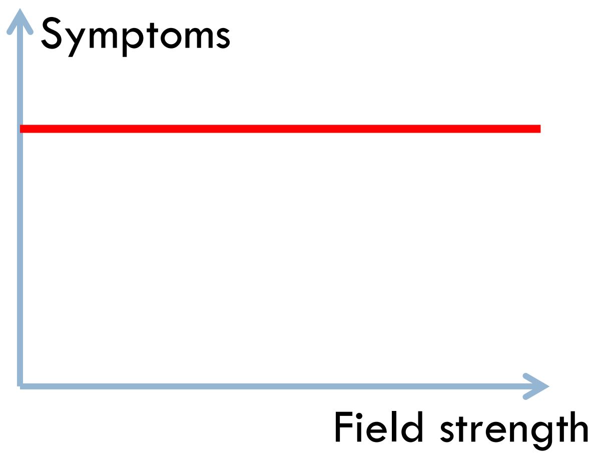
Later it turns out that the powder consisted of harmless corn starch.

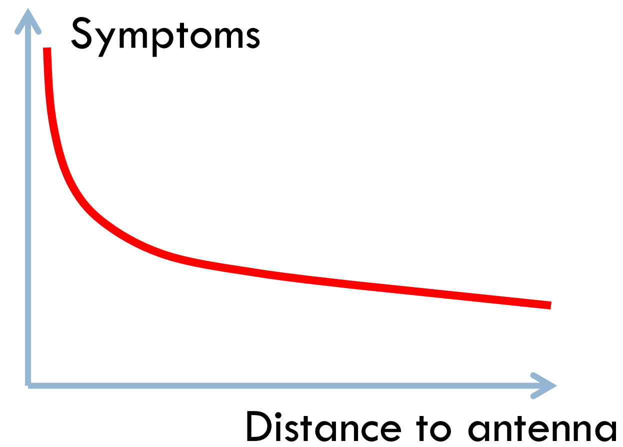
Mülligen, Switzerland, Nov. 5, 2012: People waiting to be transported to a hospital.

Swiss National Science Foundation Study

- Group of 1378 persons: Exposure to microwave fields were monitored 24 h per day for 1 week by a portable device.
- No correlation between field strength and health problems.
- No correlation between sleep quality and field strength in sleeping room.
- By far the highest field strength results from a cellular phone in operation. The field strength of wireless phones, wifi networks and basis-antennas is much weaker.
- The peak field exposure due to a cellular phone held at the ear is a factor 1’000 to 100’000 larger than due to far-field sources.
- The highest exposure occurs in public transport, when several people use their cellular phone.

The Nocebo dilemma





- Peak field strength of distant antenna is negli-gible compared to mobile phone close to body.
- Strategy to minize nocebo effect:
  Minimize number of antennas, keep them at large distance.
- Strategy to minimize potential long term health hazards:
  Many antennas at short distance to minimize the required emitting field strength of mobile phones.
- In the city of Basel, Switzerland, the authorities have recently changed the strategy:
  Many antennas in residential areas to minimize the field strength.

24 h hour cumulative exposures for typical users

Organ (24 h exposure)	GSM use (mJ/kg)	UMTS use mJ/kg	DECT wireless phone (mJ/kg)	Far-field sources (mJ/kg)	Percentage far field exposure for GSM	Percetage far field exposure for UMTS
Full body	111	0.7	27	35	20%	56%
Brain (grey)	1002	5	197	42	3.4%	17%
Hypothalamus	1109	5	187	27	2.0%	12%
Nervous tissue	23	0.09	4	7	20.6%	63%
Bone marrow	46	0.2	9	20	26.7%	68%
Testicles	0.7	0.001	0.03	76	99%	100%

Source: Report published by the Swiss Federal Office for the Environment, June 2014

Cell culture effects: What to expect?

- S – T intersystem exchange:
  - affects chemical reaction yields
  - does not induce new chemical reactions.

$$H = \mu_B \cdot (g_1 \cdot S_1 \cdot B + g_2 \cdot S_2 \cdot B) + \sum_i a_{i1} \cdot I_{i1} \cdot S_1 + \sum_i a_{i2} \cdot I_{i2} \cdot S_{21}$$

- S – T intersystem exchange is caused by:
  - Hyperfine coupling
  - $g_1 \# g_2$
  - Spin – orbit coupling (L ·S term, L = orbital angular momentum)
  - Exchange interaction
  - Static and quasi-static magnetic fields (incl. geomagnetic)
  - HF electromagnetic fields

Effects are possible

- when external static fields are of the order or larger than the internal S – T exchange fields (>100 nT).
- when HF fields are at resonance and cause population modifications within the singlet lifetime τ. This results in

$$H(nT) \geq \frac{6}{\tau(\mu\sec)} \qquad E(V/m)^{*} \geq \frac{1.8}{\tau(\mu\sec)}$$

(* in air)

Resonant effects are expected in the range 300 kHz – 150 MHz. The threshold for broadband radiation in this frequency range is more than an order of magnitude higher. For higher frequencies no effect is expected.

Assessment by a panel of biologists, medical doctors, public health officials and electrical engineers

Assessment of Evidence for biological effects of weak high-frequency radiation

Swiss Federal Office for the Environment, June 2014

Effect	Exposure	Assessment of Evidence (based on replication studies)
Tumors in the brain	Longterm and intense use of cell phone	limited
Behavior of childern and adolescents, feeling and symptoms	Emitter installations	insufficient
	Use of cell phone by child and mother (incl. prenatal)	insufficient
	Daily use of cell phone	insufficient
	Short term: cell phones and emitters (< 1 h)	inexistent
Fertility (sperma quality)	Daily cell phone use	limited
Brain currents	Daily cell phone use (< 8 h)	sufficient
Brain metabolism	< 1 h cell phone exposure	limited
Co-carcinogenic in animal experiments	> 0.9 W/kg	limited
Blood - brain barrier	< 0.1 W/kg	insufficient
Direct DNA damage	> 2 W/kg	insufficient
Indirect DNA damage by coexposure to mutagens	> 2 W/kg	limited
Cell proliferation	> 1 W/kg	insufficient
Apoptose (cell self-destruction)	> 1.6 W/kg	limited
Oxidative stress (reactive oxygen species)	> 2 W/kg	limited
Gene and protein expression	undefined	limited

Comments

- SAR (absorbed power per kg) is the wrong criterion. S – T interchange has nothing to do with dissipative processes.
- The correct exposure parameter is magnetic field, not electrical field or SAR.
- The gold standard in physics is not replication, but verification of a model prediction.
- The huge body of data obtained without guidance by a model is of very limited significance.

Conclusions

- Weak effects of stationary, quasi-stationary and high frequency magnetic fields on biochemical reaction pathways have to be expected. Effects of high frequency electrical fields can be excluded.
- The experimental evidence for such effects in cell cultures and biological systems is weak. For non-biological systems reproducible, but unspectacular effects have been found.
- No negative effects on human health have been conclusively demonstrated.
- Further progress depends on a close interdisciplinary cooperation between physicists, biochemists, microbiologists and medical doctors.