Weak-field magnetosensitivity cursed and blessed by the electron-electron dipolar coupling

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Magnetic field effects due to the Radical Pair Mechanism (RPM) are in principle well-understood and have been amply studied in chemical model systems. Yet, the question if radical pair processes could evoke significant magnetic field sensitivity in living systems in response to weak, geomagnetic-like magnetic fields is controversial. While in birds and a few other species, a compass sense has been attributed to a radical pair recombination reaction in the flavo-protein cryptochrome, it is unclear if the model can truly deliver the required sensitivity in a noisy biological environment.

The magnetosentivity of radical pair reactions in weak magnetic fields is predominately inhibited by two factors: fast spin relaxation, in particular in radical pair systems involving reactive oxygen species (ROS), which are prevalent throughout biology; and the suppressive effect of inter-radical interactions, such as the unavoidable electron-electron dipolar (EED) interaction. In particular, the latter has mostly be neglected from theoretical treatments. This question has however gained new impetus as the previously assumed mutual compensation of EED and exchange interaction appears to not be able to mitigate this issue in cryptochromes.

Here, I will show how the ostensible issues and challenges of the RPM in the context of biological magnetic field effects can be overcome by:

a) three-radical systems [1-2,5] for which the (primary) radical pair undergoes a spin selective scavenging reaction with a third, initially uncorrelated radical (a phenomenon dubbed the chemical Zeno effect),
b) three-radical systems coupled via the electron-electron dipolar interaction as their predominant interaction mode [3-4], and thus undergoing spin dynamics not as a consequence of hyperfine interactions (such as for the RPM) but their mutual dipolar coupling,
c) externally driven radical pair systems, for which the inter-radical distance is modulated to induce Landau-Zener-like non-adiabatic transitions in a magnetic-filed sensitive manner, thereby overall supporting the notion that a live, i.e. externally driven magnetoreceptor, could be markedly more sensitive than its "dead", i.e. static, counterpart.

I will demonstrate how these effects can enable significant MFEs in weak magnetic fields in biological radical pairs, partly in the presence of swiftly relaxing radicals, such as ROS. For illustration, I will focus on the photo-reduction and reoxidation pathways in cryptochromes [5], with additional references to adult hippocampal neurogenesis and hippocampus-dependent cognition in mice, which are impaired in hypomagnetic fields [6], and lipid peroxidation.

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