A Biomagnetic Sensory Mechanism
Based on Magnetic Field Modulated Coherent Electron Spin Motion

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Electron transfer processes which generate radical pairs in coherent electron spin states (singlet or triplet) are affected by weak magnetic fields [Schulten et al., Z. physik. Chem. Neue Folge 101 (1976) 371]. Based on this finding we suggest a reaction mechanism for a chemical compass which exhibits a sensitivity on the orientation of the geomagnetic field originating from an anisotropy of the hyperfine interaction experienced by unpaired electron spins in a redox process. It is argued that such mechanism may explain the ability of many biological species to orient themselves in the geomagnetic field.


Over the past decade evidence has accumulated that some living organisms are able to detect both the presence and the direction of the earth's magnetic field [1,2]. In addition to controlled cage experiments with both passerines and non-passerines [3,4] and homing experiments with pigeons
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Eqs. (2) and (3) are to be supplemented by the initial conditions \( n(t=0) = 1 \) and \( q(t=0) = 0 \). The percentage change of the product \( X \) can be written

\[
AX = X(t \to \infty) - 1 = k_X \tilde{n}(0) - 1
\]

where \( \tilde{n} \) denotes the Laplace transform of \( n(t) \). We assume for an illustration of our model \( k_X = k_T = k \) as in this case Eq. (2) can be solved analytically. Defining the branching ratio of the reaction of \( ^1Z \) to \( ^1(2A^- + 2D^+) \) and to \( ^1X \) by \( \alpha = k_x/k_X \) the solution can be written

\[
X(t \to \infty) = \left[ 1 + \alpha - \alpha \sum_{m} \frac{|\langle m| Q_\alpha |n \rangle|^2}{1 + i (\epsilon_m - \epsilon_n)} \right]^{-1}
\]

\[
= [1 + \alpha T(t \to \infty)]^{-1}
\]

where \( |m\rangle, \epsilon_m \) are the eigenstates and eigenvalues (in units of \( k \)) of the radical pair Hamiltonian and \( T(t \to \infty) \) denotes the yield of triplet products \( ^3T \) defined in [1].

We have restricted explicit calculations to radicals having identical isotropic \( g \)-values and assumed that only one of the radicals, i.e. either \( 2A^- \) or \( 2D^+ \), interacts with a single nuclear spin \( I \) (1) characterized by an axial symmetric hyperfine tensor \( (A_{xx}, A_{yy}, A_{zz}) \). Thus

\[
H = g \mu_B \cdot (S_1 + S_2) + I_z A_{zz} S_{zz}
+ (I_x S_{zz} + I_z S_{xx}) A_{xx}
\]

where \( B \) denotes the earth's magnetic field which we chose 1 Gauss in magnitude. The neglect of any exchange interaction in [6] can be shown to overestimate the percent change of \( X(t \to \infty) \) slightly [7]. The inclusion of more than one nuclear spin in [6] is not expected to change the qualitative behaviour of the system.

In Figs. 1 and 2 we have presented some typical results for \( X(t \to \infty) \) and \( T(t \to \infty) \) as a function of \( \theta \), the angle of the magnetic field with respect to the hyperfine symmetry axis (z-axis). It is interesting to note from Figs. 1 and 2 that changes of up to 33% are obtained for \( X(t \to \infty) \), viz. for the choice \( A_{xx} = 0, A_{yy} = 4 \) Gaus). This demonstrates convincingly that an anisotropic hyperfine interaction can be made sufficiently sensitive to angular changes of an external field in order to serve as a chemical compass.

Of interest is the angular acuity predicted by the angular dependence of \( X(t \to \infty) \) or \( T(t \to \infty) \). When \( A_{xx} \) is comparable in magnitude to \( A_{yy} \) most of the angular variation occurs over only a narrow range of \( \theta \), about 30°. Lacking any knowledge of \( k \) and \( \alpha \) we have chosen rather arbitrarily the values \( 10^{-3} \text{ns}^{-1} \) and 10, respectively. We note, however, that increasing the branching ratio enhances the angular acuity (see below) but decreases the absolute concentration of \( ^1X \). Shortening of the lifetime of the radical pair diminishes the angular percentage change, i.e. decreases angular acuity.
Fig. 1. Angular dependence of the yield of \( \chi \); \( \theta \) is the angle between the field direction and the \( z \)-axis. Values of the parameters used are: \( k = 10^{-4} \text{ nS}^{-1} \), \( \alpha = 10 \), \( B = 1 \text{ Gauss} \), \( A_{zz} = 4 \text{ Gauss} \); \( A_{xx} = 10 \text{ Gauss} \), \( A_{yy} = 5 \text{ Gauss} \), \( A_{zz} = 0 \).

Fig. 2. Angular dependence of triplet yield \( T(\infty) \); \( \theta \) is the angle between the field direction and the \( z \)-axis. Same parameters as in Fig. 1.

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References