In-vivo biomagnetic characterisation of the American cockroach

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We present a quantitative method, utilising a highly sensitive quantum sensor, to determine dynamics of magnetic materials in biological samples at room temperature. The method is applied to American cockroaches and reveals magnetic deposits with strikingly different behaviour in alive and dead insects. The observed dynamics allows for determination of physical properties of the sub-micron size deposits and matter around them despite their small volumes. Our work fills the gap between behavioural experiments on insects in magnetic fields and characterisation of magnetic materials in their bodies. We argue that the magnetic materials are surrounded by a glassy environment with high viscosity that renders simple forms of magnetic compasses too slow to be of biological significance.

I. INTRODUCTION

Many species are capable of perceiving the world through senses inaccessible to humans. Polarisation vision of marine species [1] or magnetic field detection by migratory birds [2] being two well-known examples. Magnetic sensitivity is in fact common to a wide range of organisms, ranging from bacteria to higher vertebrates, and has evolved to a fine-tuned sensory system that maybe even takes advantage of quantum coherence [3]. Insights into magneto-reception mechanisms and biomagnetism, magnetic fields that originate in biological systems, not only allow us to understand better different ways of visualising the world but may also find applications in improved man-made sensors inspired by their biological counterparts.

Here we demonstrate a non-invasive method that allows for continuous magnetic field measurements taking advantage of the high precision of atomic magnetometers [4]. The method is applied to study magnetic fields generated by American cockroaches (Periplaneta americana). Our study reveals presence of magnetic materials in their bodies exhibiting distinct dynamics in alive and dead cockroaches. After magnetisation of alive insects, we observe exponential magnetic field decay to a remnant value, with a decay time of 50 ± 28 minutes. In contradistinction, an average demagnetisation of dead cockroaches displays a much longer decay time of 47.5 ± 28.9 hours.

This clear difference in magnetic field decay is explained by Brownian rotations of magnetic materials in different viscosity environments. Fits of this model to the measured data reveal magnetic particles with radius on the order of tens to hundreds of nanometers. The particles are embedded in a glassy environment which experiences two orders of magnitude viscosity increment between alive and dead cockroach. Additional hysteresis measurements are compatible with multi-domain magnetic materials or single-domain greigite (Fe$_3$S$_4$) but not magnetite (Fe$_3$O$_4$).

Several behavioural experiments have demonstrated that cockroaches and other insects are capable of magneto-reception [5–8]. A different set of experiments found and characterised magnetic particles in insect corpses [9–12].

FIG. 1. Sketch of the experiment. (a) American cockroaches were placed in a strong magnetic field aligned perpendicular to the thorax as illustrated by the green lines. Using an atomic magnetometer we monitored the dynamics of the magnetic field generated by the magnetised insects. (b) The magnetic field is very close to the field of magnetic dipole normal to the thorax.
Our data and model show that these magnetic particles cannot be responsible for magnetic sensing. Their motion in high viscosity environment is too slow to be biologically useful. Hence, our present experiment provides support for other forms of magneto-reception, e.g. the radical-pair mechanism [13, 14].

II. RESULTS

The general idea of our experiments is depicted in Fig. 1. Our setup and detailed methodology are described in the Materials and Methods section. In short, magnetised cockroaches were measured with an all-optical Caesium atomic magnetometer with periodically moved sample tracking the temporal dependence of the magnetisation. An exemplary set of measurement results is presented in Fig. 2. We conducted 15 measurements, each lasted longer than 10 hours: 8 measurements on alive cockroaches and 7 on the dead ones. Additionally, more than 10 shorter experiments were conducted (2 – 5 hours) confirming the trends described below, but are excluded from statistical analysis due to different experimental conditions.

All insects produced measurable magnetic fields. Seven out of eight alive cockroaches gave rise to exponential magnetic field decay with an average decay time of 50 ± 28 minutes. For one alive cockroach we observed a weak stable-in-time signal and this dataset is not included in the average calculation. For another alive cockroach we observed magnetisation revival after the exponential decay, see Appendix. All measured dead cockroaches gave rise to a stable in time magnetic field similar to data presented in Fig. 2. The decay times have the average of 47.5 ± 28.9 hours.

In order to gain further insight into the origin of the observed magnetism we conducted a remanent hysteresis measurement the results of which are presented in Fig. 3.

A. Model

We model the observed decays with Brownian rotations of magnetic materials. The variation in the decay times from alive and dead cockroaches is explained by post-mortem increase in viscosity of the environment of the magnetic particles. Different ratios of initial magnetisation of alive and dead cockroaches follow from varying degree of alignment of the magnetic particles in the magnetising field.

Let us assume that the $i$th magnetic particle has magnetic dipole moment $\vec{\mu}_i$. Initially the cockroaches are magnetised along $z$ with macroscopic magnetic moment $M_z = N\langle\mu\rangle + A$, where $N$ is the total number of rotating particles, $\langle\mu\rangle$ is the mean dipole moment and $A$ is an offset value due to non-rotating magnetic materials. Diffusion causes rotations of the magnetic deposits, and due to the random character of thermal forces components of the macroscopic moment orthogonal to $z$ vanish, $\langle M_x \rangle = \langle M_y \rangle = 0$. The $z$ component decays as now the $i$th rotated microscopic moment contributes with the projection $\mu_i \cos \theta_i$ along the $z$ axis. It is convenient to first consider the contribution to

![FIG. 2. Magnetic field decay from magnetised American cockroaches.](image-url)

Black dots show the measured time dependence of the magnetic field for alive cockroaches and blue triangles show this dependence for the dead ones. Different panels present exemplary data for different insects. Altogether we conducted 15 measurements lasting longer than 10 hours each and additionally more than 10 shorter measurements. The thick red lines are the exponential fits to the data: solid for alive cockroaches and dashed for dead ones. The decay time of the magnetic field is (a) 25 mins [82.6 hours], (b) 30 mins [24 hours], (c) 71 mins [36.3 hours] for alive [dead] cockroach. The average decay time over all measurements is 50 ± 28 mins (47.5 ± 28.9 hours) for alive (dead) cockroaches. The offset magnetisation of 0.38 $\mu$G (thin dashed line) is attributed to the cockroach container dominating the signal for unmagnetised cockroaches. Note that the vertical scale of panel (a) is ten times bigger than the ones for the other panels.
the average macroscopic moment from the particles with the same volume. For Brownian rotations the average cosine
at time $t$ is well known and given by the exponential decay: $\langle \cos \theta \rangle = \exp(-t/\tau)$, where the decay time, $\tau = 1/2D_r$, is the inverse of the doubled rotational diffusion coefficient. For simplicity we assume spherically shaped rotating deposits and the decay time reads:

$$\tau_V = \frac{3V \eta}{k_B T},$$

where $V$ is the hydrodynamic volume of the deposit, $\eta$ viscosity of its environment, $T$ denotes the environment’s temperature and $k_B$ Boltzmann constant. Smaller magnetic particles give rise to a faster decay and they also produce a weaker magnetic field as $\mu_i = M_s V_i$, where $M_s$ is the saturation magnetisation. The macroscopic moment is obtained by additional averaging over the volumes and reads $\langle M_z \rangle = N M_s \int f(V) V \exp(-t/\tau_V) dV + A$, where $f(V)$ is the volume distribution. We take the exponential distribution $f(V) = (1/V) \exp(-V/V)$, with $V$ being the average volume, and note that similar results are obtained with a log-normal volume distribution. The average macroscopic moment can now be integrated to the closed form:

$$\langle M_z \rangle = \frac{2N \bar{\mu} t}{\tau_V} K_2 \left( 2 \sqrt{t/\tau_V} \right) + A,$$

where $\bar{\mu} = M_s \bar{V}$ and $K_2(x)$ denotes the modified Bessel function of the second kind.

For the degree of alignment of magnetic particles in the magnetising field we treat their rotation as overdamped harmonic oscillators. This is a suitable approximation in the highly viscous environment and one verifies that our estimated parameters are consistent with this assumption. Thermal effects are neglected due to the much higher magnetic interaction energy. In the overdamped regime, the angle between magnetic moment and the external field (counted from the field direction) changes as $\theta_t = \theta_0 \exp(-t/t_\odot)$, where $\theta_0$ is the initial angle and the alignment time $t_\odot$ reads (see Appendix):

$$t_\odot = \frac{6\eta}{M_s B}.$$

Note the independence of the particle size. Since unmagnetised cockroaches show no magnetic field, we assume a uniform in space distribution of initial magnetic moments. It follows that at time $t$ the distribution of angles is still uniform, but in a smaller range $\theta_t \in [0, \theta_{\text{max}}]$, where $\theta_{\text{max}} = \pi \exp(-t/t_\odot)$. This leads to the $z$ component of the macroscopic dipole moment being diminished by a factor of $\cos^2(\theta_{\text{max}}/2)$ as compared to the value when all magnetic moments are aligned.

In our experiments, the cockroaches were initially magnetised for 20 minutes and hence we use this number for $t$ in $\theta_{\text{max}}$. The saturation magnetisation is chosen as $M_s = 3 \times 10^5$ A/m, with the order of magnitude matching magnetite and greigite. After magnetisation it then takes 2 minutes to mount the cockroach container in the magnetometer during which Brownian rotations cause partial demagnetisation according to Eq. (4). At this stage we fit the model to match the ratio of initially measured magnetisations as well as the decay times. As a result we obtain the viscosity of the environment in alive insects on the order of $10^5$ Pa sec. For the dead animals the environmental viscosity increases.

FIG. 3. Hysteresis measurements on dead cockroach. The red dots show measured data of remanent magnetic field as a function of applied magnetic field. The blue curve represents a fit to the data obtained with the software package HysterSoft [15] using the Preisach model. The black curve is an exemplary hysteresis giving rise to our measured remanent hysteresis curve.
markedly to $10^7$ Pa sec. The radius of magnetic particles is typically in the range $10 - 100$ nm. Two datasets could not
be fit with a single exponential volume model but were consistent when a bimodal volume distribution was assumed
with some particles exceeding 100 nm radius. This is the case with the data shown in the left panel of Fig. 2 which
intuitively can be understood as follows. The small particles decay faster and this combined with the effect of the large
viscosity difference leads to the big discrepancy between initial magnetisations of alive and dead insect. However, this
decay is too fast to match the experimental decay times and therefore larger particles have to be introduced.

III. DISCUSSION

The obtained high values of viscosity agree with estimations for cytoskeleton inside cells, which was suggested to
be a glassy material [10]. The origin of high viscosity in our approach can be traced back to the alignment in the
magnetising field. In most of the datasets the initial field from the dead cockroach is below the initial field of the alive
cockroach. Since decay times of magnetic field from the dead cockroaches are larger than those from alive insects the
only explanation is the partial alignment of the magnetic materials in the dead cockroach within the comparatively
short magnetisation time frame. The order of magnitude of the viscosity can be estimated from Eq. (3). For the
effect of partial alignment, time $t_0$ has to be comparable with $20$ minutes and hence viscosity of the environment in
the dead animal should be on the order of $10^7M_B B \sim 10^7$ Pa sec.

The increment in viscosity of the environment inside alive and dead cockroaches follows from the expected physio-
logical changes. The dead cells permanently dehydrate causing an increase in volume fraction of cytoskeleton which
in turn increases environmental viscosity. Our measurements are consistent with a viscosity increase of two orders of
magnitude. The increase in viscosity has already been independently observed inside dying cells [17].

We note that the estimated size of magnetic materials is in the range of biogenic clusters of magnetic particles
that were extracted from two species of termites [12]. This might not be a coincidence as termites are eusocial
cockroaches [18]. They belong to the same order Dictyoptera and have closely related symbionts. Nevertheless, we
emphasise that our experiments do not prove biogenic magnetism because environmental ferromagnetic contaminants
could still be present in the tissues [19].

The hysteresis measurement (see Fig. 3) reveals a small value of the coercive field, $40 \pm 6$ G. This is typical for
multi-domain materials or single-domain greigite [21], but not single-domain magnetite found in various other animals
for which the corresponding coercive field is about $400$ G [20]. We pursue further the hypothesis of single-domain
greigite. Ref. [22] identified a black region in the cockroach, Eublaberus posticus, hindgut rich in metal sulphides.
Unknown organisms producing $H_2S$ were also found in the flora around the black band. Greigite could form there
naturally by reduction of iron in $H_2S$ rich environment with low oxygen level. Since guts are well-nerved one can even
speculate that cockroaches could sense magnetic field based on greigite deposits connected to nerves in their hindgut.

Some evidence already exists for magnetic sensing ability in cockroaches. Cockroach mobility increases when it is
placed in an Earth-strength magnetic field ($\sim 0.5 G$) with periodically varying direction [5, 6]. Furthermore, magnetic
deposits of sizes similar to our estimations were reported in the specimen of dead bees, ants and termites [8]. It is
therefore tempting to conjecture that these deposits are responsible for magnetic sensing. Our in-vivo experiments
disprove this conjecture. Although a single-domain greigite particle of radius $50$ nm has the magnetic energy in the
Earth’s magnetic field almost $100$ times above the thermal energy at room temperature, the determined high viscosity
causes its alignment time in the order of hours. This form of compass is hence too slow for biological purposes.
Other mechanisms might be responsible for magneto-reception, such as the radical pair model for which independent
experimental support exists in cockroaches [18, 14].

In conclusion, we realised a non-invasive method of magnetic field measurements applicable to biological systems
at room temperature. The method employs an atomic magnetometer with periodically moved sample. When applied
to American cockroaches it allows quantitative estimation of sub-micron size magnetic particles in their bodies and
clearly discriminates between dead and alive insects. We propose that its physical origin lies in the post-mortem
change of the viscous intracellular environment surrounding the particles. More generally, this technique can be
used to test physiological processes or gain insights into the study of stochastic processes driving the motion of
biomolecules or magnetic tracer substances inside cells. Independent of any potential magneto-receptive suitability,
the characterisation of physical properties of magnetic particles found in biological tissues of various species, even in
the human brain, is worth studying. It may help to establish their physiological purpose which is largely unknown
and to distinguish biogenic precipitates from magnetic contaminants.
**IV. MATERIALS AND METHODS**

**A. Experimental procedure and data collection**

Alive adult female and male cockroaches were kept in transparent insectaria with unlimited water and a diet consisting of cat food pallets and photoperiod of 12 light : 12 dark hours. Before the experiment the insectarium was placed in a 4°C environment in order to immobilise the insects. The experiments on dead cockroaches took place at least 2 days after death and the dead cockroaches were kept in the 4°C environment to slow down putrefactive processes. The death was induced by a nitrogen gas atmosphere and thereafter the cockroaches were washed in an ultrasonic bath confirming interior origin of the observed magnetic signal. Every immobilised or dead cockroach was placed in a plastic bag which in turn was put in-between two characterised permanent magnetic plates producing a field of 3 kG at the cockroach location. The direction of induced dipole moment is indicated in Fig. 1. After 20 minutes of magnetisation the sample was mounted on a motorised translation stage inside the optical Caesium atomic magnetometer as shown in Fig. 4. We periodically varied the distance between the sample and the Cs cell for at least 10 hours. One period takes 20 seconds. The recorded data-points are obtained by averaging over 20 periods. Each data-point has a magnetic field uncertainty of 0.08 µG. We verified that the bag alone produces a stable magnetic field over the timespan of our experiment (0.38 ± 0.08 µG).

**B. Atomic magnetometry**

A scheme of our experimental setup is depicted in Fig. 4 and described in detail in reference [23] for a similar setup. The highly sensitive optical Caesium atomic magnetometer is based on nonlinear magneto-optical (Faraday) rotation, where the polarised incident laser beam is altered by atomic Cs vapour subjected to an external magnetic field.

**C. Measurements of remanent hysteresis**

We placed a dead cockroach in between two N52 grade neodymium permanent magnet plates so that the applied magnetic field is oriented as in Fig. 1. By changing the separation between the plates the magnitude of the magnetic field at the cockroach position was varied. The magnetic field variation over the cockroach body is at most 15%. The magnetisation time is 10 minutes. We start with an external field equal to 750 G and continue along the hysteresis loop.
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Appendix A: Magnetic field revival

The theory outlined in the main text explains an exponential magnetic field decay which was observed for most cockroaches. For this one insect, however, we have seen a revival of the magnetic field as shown in the figure.

![Magnetic field revival graph](image)

Appendix B: Fasted cockroach

We verified that the food pallets given to cockroaches can be magnetised and therefore conducted the experiment with fasted cockroach in order to exclude the hypothesis that the observed decay is due to ingested magnetism of the food. The mean food transit time was determined to be 20.6 hours, with a part of each meal retained in the crop for up to 4 days [24]. We therefore fasted the cockroach for 7 days, giving it only water, and found that this had no effect on the decaying magnetic field. This is not a conclusive proof of biogenic magnetism because environmental ferromagnetic contaminants could still be present in the tissues [19].

Appendix C: Alignment time

Consider a spherical particle endowed with magnetic moment $\vec{\mu}$ and surrounded by an environment with viscosity $\eta$ at room temperature $T$. If the particle is subject to an external magnetic field $\vec{B}$, its rotational motion is described by the Newton law:

$$I\ddot{\theta} = -f\dot{\theta} - \mu B \sin \theta + T.$$  \hspace{1cm} (C1)

Here $\theta$ denotes the angle between $\vec{B}$ and $\vec{\mu}$ (counted from $\vec{B}$), $I$ stands for the moment of inertia of the sphere, $I = \frac{2}{5}\rho VR^2$, and $f$ is the rotational friction coefficient, $f = 8\pi\eta R^3$. The next term gives magnetic torque and the last term is the thermal torque whose influence we will ignore here because the strong aligning field of 3 kG gives rise to $\mu B \gg kT$ even for very small magnetic moments.

Our aim is to calculate the time it takes the particle to align with the field, $t_\odot$. Note that $t_\odot$ is longer than the alignment time $t_\downarrow$ obtained when the magnetic torque is replaced by a stronger torque. Similarly, $t_\odot$ is shorter than the alignment time $t_\uparrow$ obtained if the magnetic torque is replaced by a weaker torque. We show a simple upper and
lower bound on the strength of the magnetic torque leading to alignment times that differ only by a constant factor of order one. Hence the obtained formula also holds for $t_\odot$.

Consider first the stronger torque $\mu B \sin \theta \leq \mu B \theta$. The problem reduces to the damped harmonic oscillator. Due to the high estimated viscosity $f^2 - 4I\mu B \gg 0$, the oscillation is overdamped with the general solution

$$\theta_t = \left( \theta_0 - \frac{r_- \theta_0}{r_- - r_+} \right) \exp(r_-t) + \frac{r_- \theta_0}{r_- - r_+} \exp(r_+t),$$

where $\theta_0$ is the initial angle and

$$r_\pm = \frac{1}{2} \left( -\frac{f}{I} \pm \sqrt{\frac{f^2}{I^2} - 4\frac{\mu B}{I}} \right).$$

Since $(f/I)^2 \gg 4\mu B/I$ we simplify:

$$r_+ = -\frac{\mu B}{f},$$

$$r_- = -\frac{f}{I} + \frac{\mu B}{f}.$$

Furthermore, both $r_\pm$ are negative with $r_- \ll r_+$ and therefore $\exp(r_-t)$ quickly decays to zero. The long time dynamics is governed by the decay $\exp(r_+t)$, which admits alignment time:

$$t_\downarrow = \frac{\mu B}{f} = \frac{6\eta M_s B}{\theta_0}.$$
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