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Magnetic material in head, thorax, and abdomen of *Solenopsis substituta* ants: A ferromagnetic resonance study

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Abstract

Ferromagnetic resonance temperature dependence is used to study the magnetic material in smashed head, thorax, and abdomen of *Solenopsis substituta* ants. These three body parts present the five lines previously observed in other social insects. The magnetic material content is slightly higher in heads with antennae than in abdomen with petiole. Isolated nanoparticle diameters were estimated as 12.5 ± 0.1 and 11.0 ± 0.2 nm in abdomen with petiole and head with antennae, respectively. The presence of linear chains of these particles or large ellipsoidal particles are suggested. A bulk-like magnetite particle was observed in the thorax. The Curie–Weiss, the structural–electronic and ordering transition temperatures were obtained in good agreement with those proposed for magnetite nanoparticles.

Keywords: Fire ants; FMR; Magnetic nanoparticles; Magnetic volume; Temperature transitions

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1. Introduction

Animals use several orientation mechanisms, among them those based on the geomagnetic field as a cue. Magnetoreception is a sophisticated orientation mechanism, involving a magnetoreceptor, connected to the nervous system with signal amplification. Under the physical point of view, the ferromagnetic hypothesis [1,2] is the most accepted one. It is based on the presence of ferromagnetic particles as the magnetoreceptor and supported by the detection of magnetite particles in a wide variety of animals, from insects [3,4] to humans [5,6]. Recently, a model was proposed considering the interactions among closely spaced clusters of superparamagnetic magnetite present in the upper-beak of homing pigeons. These interactions, induced by a variable magnetic field, result in a stress on the surrounding cellular structures [7,8].

It has been demonstrated that a few insects orient with the geomagnetic field [1] and ants respond to magnetic field changes. A magnetic compass response has been shown for Formica *rufa* [9] and *Oecophylla smaragdina* foraging [10]. *Atta colombica* ants respond to magnetic reversal in the absence of sunlight cues [11]. The magnetic effects on the time for trail formation by *Solenopsis invicta* ants are not clear [12,13], however, a role for magnetic cues in determining direction during ant orientation can be suggested.

Solenopsis ants are easily found and are widely spread in Brazil. These features turn this specie an interesting model for magnetic orientation studies, as it allow comparative analysis among nests in different location and geophysical conditions.

SQUID magnetometry and ferromagnetic resonance (FMR) are useful techniques to verify the ferromagnetic

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hypothesis by localizing and characterizing the magnetoreceptor with no need for purification. FMR has the advantage of detecting only paramagnetic and ferro(i)magnetic substances and their interactions with the neighborhood. However, only relatively large amounts of magnetic material can be detected. The signal dependence on nanoparticles size, shape, and orientation, due to the anisotropy and demagnetization field contributions is an important feature [14–16].

There are few studies on magnetic materials in different body parts of social insects. It is well accepted that magnetite particles in *Apis mellifera* bee abdomen are involved in magnetoreception [17–19]. These studies were fostered by behavior assessment of trained honeybees that had magnets placed in their abdomens [20]. Susceptibility and magnetization measurements have shown typical paramagnetism with small magnetic remanence down to 4.2 K in the abdomen of adult worker honeybees while thorax and head showed an apparently diamagnetic behavior [21].

Hysteresis at 300 K of *Pachycondyla marginata* ants oriented body parts showed that the most relevant contribution to the ant saturation magnetization comes from the antennae. This sensory organ appears as a good candidate to a magnetoreceptor [22], once their migration was observed to be significantly oriented 13° relative to the magnetic North–South axis [23].

Previous FMR studies of crushed whole *Solenopsis* sp. ants [4], intact *Neocapritermes opacus* termites [24] and abdomens of migratory ant *P. marginata* and honeybee *A. mellifera* [14,15] showed the presence of different magnetic materials. Induced Remanent Magnetization (IRM) of *Nasutitermes exitiosus* [25] and FMR of *N. opacus* [24] indicated more magnetic material present in the thorax plus abdomen than in the termite head.

Magnetic material identification, localization, and characterization in ant body parts are necessary to the understanding the magnetoreceptor function. This paper reports the *S. substituta* ants abdomen with petiole-ABD, head with antennae-HEAD and thorax with feet-THOR FMR spectra dependence on temperature.

2. Materials and methods

Solenopsis substituta workers were collected in Fernando de Noronha, Pernambuco, Brazil, carefully washed with 70% (v/v) ethanol, until no particles were observed under a optical microscope (Micronal, AO-101 model), and preserved in 70% (v/v) ethanol. Just before measuring, they were dried on a filter paper for about 3 h at room temperature and separated into three parts: ABD (290 units), HEAD (250 units), and THOR (250 units), dried at 50 °C for 1 h, smashed, and transferred to quartz ferromagnetic resonance (FMR) tubes.

Measurements were performed with a commercial X-band EPR spectrometer (Bruker ESP300E) operating at a microwave power of 4 mW with a 100 kHz modulation frequency and a ~2 Oe modulation field amplitude, from 3 K to room temperature (RT). Spectra double integration was obtained using WINEPR software (Bruker).

Body part spectra were fitted using Origin 6.0 (Microcal) with two or three components: the high field (HF and HF′) and the low field (LF). Gaussian and Lorentzian derivative-shaped lines were used to obtain the temperature dependence of the resonance linewidth (ΔH_{pp}), resonance field (H_R), and absorption area (A) of HEAD and ABD spectra. Lorentzian (HF) and Dysonian (LF) shaped lines were used for THOR spectra. The Dysonian line is the combination of absorption and dispersion Lorentzian curves, expressed by Eq. (1) as a function of R_{ad}, the absorbed and dispersed microwave energy rate.

$$\begin{aligned} {}^{D}Y'(H) = B\{\{[1-(2(H-H_R)/\Delta H_{\mathrm{pp}})^2] \\ \times R_{\mathrm{ad}} - 4(H-H_R)/\Delta H_{\mathrm{pp}}\} \\ /[1+(2(H-H_R)/\Delta H_{\mathrm{pp}})^2]^2\}, \end{aligned} \tag{1}$$

where H_R and ΔH_{pp} are the parameters of the Lorentzian absorption derivative.

3. Results

The *S. substituta* ant parts spectra dependence on temperature is shown in Fig. 1. Each spectrum is composed of at least five components. An asymmetric line at $g = 4.3$ which intensity increases as temperature decreases, is characteristic of magnetically isolated high spin $S = 5/2$ Fe^{3+} ions in low-symmetry environment [26]. The narrow line at $g = 2$ is related to free radicals resulting from biological processes [27]. In the ABD and HEAD spectra, a broad line (~1000 Oe linewidth) at $g \sim 2$, called HF, is easily observed. Superimposed on this line, HF′ (about 300 Oe width) is resolved only at low temperatures. At RT a low field broad component (LF) is observed as a shoulder around $g = 4.3$ in the ABD and HEAD spectra, while in the THOR spectra, it is at $g = 18$ (position field where the amplitude is null) with a different lineshape predominant in the whole temperature range. In Fig. 1, examples of fitted curves (FIT) with the three components described above are shown, at 50 K, RT, and 4 K for the ABD, HEAD, and THOR, respectively.

The area under the absorption curve, S, is proportional to the number of FMR resonant spins. The LF component is dominant in the THOR spectra and it spreads out to negative field values that turns difficult S calculation of these spectra. However, based on the proportionality $S \propto I_{\mathrm{pp}} \times \Delta H_{\mathrm{pp}}^2$, a lower limit, 1.1×10^9 a.u., is