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Microwave Absorption by Magnetic Nanoparticles in the Organism

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Abstract—An estimate is presented for the rate of microwave absorption by magnetic nanoparticles in the organism. The absorption takes place because of energy dissipation at ferromagnetic resonance. Based on the known solution of the Landau–Lifshits equation, the imaginary part of complex susceptibility is evaluated, which gives the absorption rate. It is shown that even under thermal isolation of the particles, their heating would be insignificant upon absorption of radiation with an energy flux density on the order of 1 mW/cm^2, and such a mechanism is unrelated to the observable effects of low-intensity microwaves.

Keywords: magnetic nanoparticles, absorption of electromagnetic waves, ferromagnetic resonance.

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Radio-frequency radiation typical of mobile phones has recently been classified as a possible carcinogen for the human organism [1]. Meanwhile, the very nature of biological effectiveness of SHF/EHF electromagnetic radiation of low intensity, ~ 1 mW/cm^2 or less, remains obscure. Various hypotheses have been discussed (for review, see e.g. [2, 3].

One of the proposed mechanisms assumes that the energy of electromagnetic fields is absorbed by biogenic magnetite nanoparticles in the organism [4]. The author envisions a microwave field as rays permeating a biological tissue with embedded nanoparticles, and shows that even at a low concentration of nanoparticles they present a substantial geometric obstacle for the rays. Further, the author calculates the absorption by nanoparticles, and concludes that it is sufficient for emergence of biological effects of low-intensity microwave radiation. However, this conclusion is erroneous. The fallacy stems from groundlessly applying the approximation of geometric optics to assessing energy absorption. Here, the real capacity of these processes is estimated. Taking that the absorption is due to energy dissipation at ferromagnetic resonance and that because of particle shape diversity the resonance frequencies reach up to mid-SHF range, the known solution of the Landau–Lifshits equation for the imaginary part of complex susceptibility shows that heating by mobile phone radiation would be insignificant even for "thermally isolated" nanoparticles. Also negligible would be a magnetostrictive effect for nanoparticles in such a field.

Single-domain magnetic nanoparticles have spontaneous magnetization and hence a permanent magnetic moment **M**. Related therewith is the mechanical moment $\mathbf{S} = -\mathbf{M}/\gamma\hbar$, where γ is gyromagnetic ratio, which for magnetite Fe_3O_4 is close to that of electron $\gamma_e \approx e/m_e c \approx 17.6 \cdot 10^6$ rad/(s G) or 2.80 MHz/G. Projection of the mechanical moment onto arbitrary axis z takes values of series S, $S-1$, ..., $-S+1$, $-S$; accordingly, the projection of magnetic moment M_z can take $2S+1$ values. In a constant magnetic field (MF) the energy level corresponding to these states splits, and the energy difference for any two neighbor levels is $\Delta e = \Delta M_z H = \gamma\hbar\Delta S_z H \approx \gamma\hbar H$. In a constant MF the magnetic moment precesses about the MF direction at frequency $\omega_0 = \Delta e/\hbar = \gamma H$. Addition of an alternating MF of $\omega = \omega_0$ gives rise to ferromagnetic resonance. This is a particular case of magnetic resonance—enhanced rate of energy exchange between the electromagnetic field and the magnetic subsystem upon coincidence of the external MF frequency and the intrinsic frequency of magnetic moment precession in the constant part of external MF.

For frequency estimation, it would be incorrect to consider a magnetic nanoparticle as a point magnetic moment in an external field **H**. The magnetic moment of a particle is the sum of atomic magnetic moments localized inside the particle, where the MF is distinct from the external one and in small external MF largely coincides with the field caused by magnetization proper.

The magnetization depends on the MF direction relative to the crystallographic axes. That is, in an external field the internal MF would depend on the directional cosines of the external field. However, the latter—the geomagnetic field for the case in point—is far smaller than the saturation magnetization; hence, single-domain nanoparticles are spontaneously magnetized along the easy axis. For this reason, the contribution of magnetic anisotropy into estimated parame-

ters of ferromagnetic resonance of nanoparticles in the geomagnetic field can be neglected.

The main factor that influences the internal MF of single-domain particles is their shape. In a body of limited size, the internal MF creates "magnetic charges" at the opposed sides that tend to attenuate the MF strength. If the internal MF H^i is uniform, which is so only in ellipsoid specimens, it can be expressed through the external field and the saturation magnetization. If the ellipse axis coincides with the field direction, then $H_i^i = H_i - N_i M_i$, where the subscript runs x, y, z; M are magnetizations and N are so-called demagnetizing factors along the respective axes.

The equation of magnetization vector motion in the Landau–Livshits form is

$$\frac{d}{dt}\mathbf{M} = -\gamma \mathbf{M} \times \mathbf{H}^i - \frac{\gamma\alpha}{M}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}^i), \qquad (1)$$

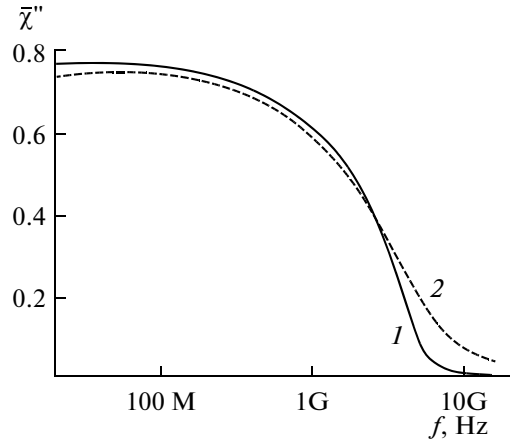
where α is dissipation parameter. The problem of dissipation of magnetization vector precession for a small ellipsoid in an RF field has known solutions [5]. The intrinsic frequency of precession, i.e. one at $\mathbf{H} = (0, 0, H_z)$ and $\alpha = 0$, in the case of particles shaped as ellipsoids of revolution ($N_x = N_y$) directed along axis z, is determined as

$$\omega_0/\gamma = H_z + (N_x - N_z)M_0, \qquad (2)$$

rather than $\omega_0/\gamma = H_z$, which would be valid in the absence of a demagnetizing effect or for spherical particles with $N_x = N_y = N_z$.

The single-domain magnetite particles found in organisms are neither very long nor very flat. The demagnetizing factors for an ellipsoid of revolution depend on the ratio a of size along z to transverse size [6]. Inasmuch as $\Sigma_i N_i = 4\pi$, it is easy to see that a demagnetizing field $(N_x - N_z)M_0$ can vary from zero to five or six M_0. For estimation, as M_0 one should take the saturation magnetization $M_s \approx 480$ G, and the constant external field should be equated to zero, because it is much weaker than the demagnetizing field. Thus, the possible frequencies of ferromagnetic resonance for magnetite single-domain nanoparticles cover a broad range from near-zero to 5 γM_s, i.e., to some 7 GHz.

The width of ferromagnetic resonance for magnetite single-domain particles on the whole is on the order of resonance frequency; i.e., there is no sharp resonance, and a particle absorbs energy quite evenly over a wide frequency range. For this reason, it is sometimes supposed that magnetite absorbs all the energy of incident SHF electromagnetic radiation [4]. Yet it is doubtful that the geometric optics approximation is appropriate here, since the radiation wavelength is far greater than the nanoparticle size. A regular way to calculate the absorption is to find the imaginary part of complex susceptibility of the particles in an external uniform MF.



Ensemble-average value of the imaginary part of complex susceptibility of nanoparticles at different levels of dissipation parameter: *1*, $\alpha = 0.1$, *2*, $\alpha = 0.5$.

If there is dissipation ($\alpha \neq 0$) in an MF $\mathbf{H} = (H_x \sin(\omega t), 0, H_z)$ a stationary regime arises in which the MF energy is transformed into heat. The specific energy absorption rate $P = \omega\chi'' H_x^2/2$ can be estimated knowing the relationship between the imaginary part of complex susceptibility $\chi = \chi' - i\chi''$ and the dissipation parameter α. This relationship ensues from solving (1) at a relatively small amplitude $H_x \ll M_0$ and is determined by

$$\chi \equiv M_x/H_x = \gamma M_0 \frac{\omega_0 + i\alpha\omega}{(\omega_0 + i\alpha\omega)^2 - \omega^2},$$

where M_x is the amplitude of x-component of magnetization. Isolating the imaginary part and substituting $\omega_0(N_z)$ from (2), we can find $\chi''(N_z)$. It is then used as follows.

Since χ'' substantially depends on $N_z(a)$, which in its turn strongly depends on nanoparticle shape, we must perform averaging. Let us take an appropriate distribution with respect to a, such as Maxwellian distribution $f(a) = 4a^2 e^{-a^2}/\sqrt{\pi}$. Then nearly 90% of particles fall into the interval of a from 0.5 to 2.0, with a maximum at $a = 1$, which is consistent with the observations of nanoparticles in organisms. The ensemble-average χ'' is

$$\bar{\chi}'' = \int_0^\infty \chi''[N_z(a)] f(a) da.$$

The dependence of $\bar{\chi}''$ on external field frequency obtained by numerical integration at $H_z = H_{geo}$ is shown in the figure for two α values. According to measurements of complex susceptibility for magnetite

(e.g. [7]), under conditions of ferromagnetic resonance, α ranges from 0.16 at 2.5 GHz to 0.25 at 24 GHz. It is evident that electromagnetic field absorption by an ensemble of microellipsoids with random shape parameter does not appreciably change in the lower frequency range, while in the SHF range of mobile phones it amounts to 0.4–0.6.

Considering that the H-part of a plane electromagnetic wave is related with the energy flux density S as $H_x^2 = 4\pi S/c$ (c is speed of light), the specific energy absorption rate (see above) can be written in the form $P = \bar{\chi}''(2\pi)^2 fS/c$, where $f \equiv \omega/2\pi$ can be taken to be 1 GHz.

On the other hand, the increment in particle temperature upon receiving heat Q is $\delta T = \delta Q/c_h$, where c_h is the heat capacity per unit volume of the particle matter. That is, the heating rate is $dT/dt = P/c_h$. The heat capacity of magnetite is about 0.65 J/(g K) or $3.4 \cdot 10^7$ erg/(cm^3 K). Substituting all the numeric data, for an electromagnetic energy flux density of 1 mW/cm^2, or 10^4 erg/(s cm^2), we obtain

$$dT/dt = (2\pi)^2 \bar{\chi}'' \frac{fS}{c_h c} \sim 10^{-4}\ \text{K/s}.$$

In other words, if the nanoparticles were thermally isolated, their temperature would have risen by one degree after 2 h of exposure. Yet the time of nanoparticle thermalization is many orders of magnitude shorter. Hence it is clear that the vanishingly small heating of nanoparticles by absorption of RF radiation energy has nothing to do with the observed biological effects of such radiation.

It has also been supposed that a biological effect might arise from hypersound—acoustical vibrations generated by magnetostriction (or relative length change) of nanoparticles in an SHF MF.

Evaluating this hypothesis, we should proceed from hypersonic attenuation in water α_d and the magnetostriction constant for magnetite. The so-called reduced attenuation factor $f^{-2}\alpha_d$ is independent of frequency in the range considered, being about 25×10^{-17} s^2/cm [8]. Then the amplitude of a hypersonic 1-GHz wave will drop e times over a distance $1/\alpha_d$ about 40 μm. On the other hand, the phase velocity of sound in water is $v = 1.483 \cdot 10^5$ cm/s, hence the sound wave length v/f at 1 GHz is close to 1.5 μm. This means that the distribution of sound waves in a biological cell around an oscillating magnetic particle is determined by near-zone conditions without damping: biophysical structures of smaller size surrounding the particle may experience vibrations of the same order of amplitude as the particle does.

However, the amplitude of striction vibrations of the particle itself is extremely small. The magnetostriction λ of magnetite depends on the applied field strength [9], reaching some $2 \cdot 10^{-5}$ at saturation about 2 kG. Taking $\lambda(H)$ to be linear in small fields, we find that the field derivative λ'_H is on the order of 10^{-8} G^{-1}.

The H-part of microwave radiation of ~ 1 mW/cm^2, even if it reaches the nanoparticles without attenuation, makes $H = 2\sqrt{\pi S/c} \sim 2 \cdot 10^{-3}$ G. Hence the compression/stretching amplitude for a particle of $r \sim 50$ nm is $x_a \sim r\lambda'_H H \sim 10^{-9}$ nm. The infinitesimality of this value testifies to the negligibility of effect.

To make this obvious, let us find the energy of vibrations of such amplitude in a volume of $\sim 1/\alpha_d^3$, i.e. in a region where the vibrations propagating from the particle have not yet faded. The energy of an equivalent oscillator of mass $m^* = \rho_{H_2O}/\alpha_d^3$ obeying $\ddot{x} + \omega^2 x = 0$ (where $\omega = \sqrt{k/m^*}$ and k is oscillator stiffness) is

$$e = kx_a^2/2 \sim 10^{-7}\, k_B T.$$

Thus the hypothesis of striction vibrations of magnetic particles should also be deemed hopeless as regards explaining the biological effects of microwaves of such intensity.

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