Vibrational Resonances in Biological Systems at Microwave Frequencies

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ABSTRACT Many biological systems can be expected to exhibit resonance behavior involving the mechanical vibration of system elements. The natural frequencies of such resonances will, generally, be in the microwave frequency range. Some of these systems will be coupled to the electromagnetic field by the charge distributions they carry, thus admitting the possibility that microwave exposures may generate physiological effects in man and other species. However, such microwave excitable resonances are expected to be strongly damped by interaction with their aqueous biological environment. Although those dissipation mechanisms have been studied, the limitations on energy transfers that follow from the limited coupling of these resonances to the electromagnetic field have not generally been considered. We show that this coupling must generally be very small and thus the absorbed energy is so strongly limited that such resonances cannot affect biology significantly even if the systems are much less strongly damped than expected from basic dissipation models.

RESONANCE ABSORPTION

The possibility that biological systems coupled to the electromagnetic field can exhibit classical resonance at microwave frequencies has long been of interest (Frölich, 1968; Maret et al., 1979; Adair, 1995), and that possibility has had an impact upon microwave regulatory considerations (Stewart, 2000). Evidence of such microwave absorption resonances has been reported (Edwards et al., 1984; Grundler and Keilman, 1983), but these results have not been replicated (Gabriel et al., 1987; Foster et al., 1987).

We posit that for resonances to have an important effect on biology, the system must absorb energy in excess of that from thermal noise. For elements acting incoherently, that noise energy will be approximately equal to kT, in which k is Boltzmann's constant and T is the Kelvin temperature. Such a significant energy transfer requirement demands long relaxation times and significant coupling strengths to the electromagnetic field. Although the dissipation mechanisms have been studied extensively (Grundler and Keilman, 1983; Dorfman and Van Zandt, 1983; Van Zandt, 1981, 1986), less attention has been paid to the electromagnetic couplings, which we consider here in some detail.

Because the biological systems that we consider will be much smaller than the wavelength of microwave radiation, which is by definition greater than 1 mm, any absorption of energy by the system must take place through the interaction of the field with the dipole moment charge distribution of the system. The absorption of energy by a resonant system from a electromagnetic plane wave through a dipole interaction can be expressed in terms of an absorption cross-section, σ_a in which (Blatt and Weiskopf, 1952),

$$\sigma_a(\nu) = 3\frac{\lambda^2}{\pi}\frac{\Gamma_s\Gamma_a}{(\nu-\nu_r)^2+\Gamma^2/4}. \qquad (1)$$

Here Γ_a is the absorption width, Γ_s is the scattering or emission width, and $\Gamma = \Gamma_a + \Gamma_s$ is the total width. The resonant frequency is ν_r, and $\lambda = c/\nu$ is the wavelength of the radiation. The cross-section σ_a is defined as the power absorption per unit incident power flux and has the dimensions of area.

The widths, $\Gamma_j = dw_j/w$, with dimensions of $1/t$ are equal to the ratios of the energy loss rate, dw_j through the process, j, to the characteristic energy, w.

If the incident power flux is I W/m^2, the power, P_a, absorbed by the system is,

$$P_a = I\sigma_a \qquad (2)$$

which will generate an increase in energy, Δw, of the resonant system where,

$$\Delta w = P_a \times \tau = \frac{I\times\sigma_a}{\Gamma_a} \quad \text{for} \quad \Gamma_a \gg \Gamma_s \qquad (3)$$

The condition, $\Gamma_a \gg \Gamma_s$ will generally obtain for biological systems of interest.

Maximal cross-section and energy transfer

Taking $\Gamma_a \gg \Gamma_s$, the maximal absorption cross-section at $\nu = \nu_r$ will be

$$\sigma_{max} = 12\frac{\lambda^2}{\pi}\frac{\Gamma_s}{\Gamma_a} \quad \text{and} \quad \Delta w = 12\frac{I\lambda^2}{\pi}\frac{\Gamma_s}{\Gamma_a^2} \qquad (4)$$

We note that this cross-section and energy deposition are independent of w, the characteristic energy of the system.

We can use this relation to estimate a maximal width for a resonance to generate a biological effect by taking the

Submitted March 1, 2001, and accepted for publication May 7, 2001.

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0006-3495/02/03/1147/06 $2.00

minimal energy deposition per oscillator as, $\Delta w = kT/N^{1/2}$ in which N is equal to the number of oscillator elements that act coherently. (For most situations that we consider, $N = 1$.) Thus,

$$\Gamma \approx \Gamma_a < \left(12\,\frac{I\lambda^2}{\pi}\,\frac{\Gamma_s}{N^{1/2}kT}\right)^{1/2} \tag{5}$$

Integrated cross-sections

The energy absorption cross-section integrated over all frequencies,

$$\int_0^\infty \sigma_a(\nu)d\nu = \frac{3\lambda^2\Gamma_s}{2} \quad \text{for} \quad \Gamma_s \ll \Gamma_a \tag{6}$$

is proportional only to the radiation width and is independent of the absorption width, which for many processes is not easily calculated.

Under some circumstances the integrated cross-section lends itself to useful limits. If the bandwidth of the incident radiation is $\Delta\nu$, the power transmitted to the resonant system,

$$P_a \le 3I\lambda^2\,\frac{\Gamma_s}{\Delta\nu} \quad \text{and} \quad \Delta w \le 3I\lambda^2\,\frac{\Gamma_s}{\Gamma_a\Delta\nu} \tag{7}$$

Radiative width

Because the biological systems of interest tend to be much smaller than the microwave wavelengths, which are by definition greater than 1 mm, the coupling of the electric dipole moment to the radiative field tends to be small, and the maximal absorption by the system will be small. I estimate Γ_s, the radiative width using classical electrodynamics. The power P radiated by an oscillating electric dipole is,

$$P = \frac{dw}{dt} = \frac{1}{4\pi\epsilon_0}\,\frac{d_0^2\omega^4}{3c^3} \tag{8}$$

in which $\omega = 2\pi c/\lambda$ is the radial frequency of the oscillator and $d_0 = qa$ is the maximal oscillating dipole moment, which I describe in terms of an amplitude (a) and charge (q) of an element with a characteristic mass (m).

With this model, I take the energy of the oscillator as,

$$w = \tfrac{1}{2}\,m\omega^2a^2 \tag{9}$$

and

$$\Gamma_s = \frac{1}{\tau_s} = \frac{P}{w} = \frac{q^2\omega^2}{6\pi\epsilon_0 mc^3} \tag{10}$$

For orientation, we note that for $\nu = 10$ GHz, $q = e$, $m = m_p = 1.67 \times 10^{-27}$ kg, $\Gamma_s = 1.34 \times 10^{-6}$ s^{-1}, and $\tau_s = 1/\Gamma = 7.5 \times 10^5$ s. Even as the lifetime of such states by radiative decay is very long, the radiative width (and thus coupling to the electromagnetic field) is very small.

Absorption width: relaxation time

The kinetic energies of moving biological elements will be lost to internal and external dissipative frictions. Moving generally in an aqueous environment such as the cytoplasm or tissue plasma, the characteristic velocities of motion are usually small, and the appropriate Reynold's number is usually much less than one. Thus, the energy transfer to that environment follows largely from viscous friction.

We consider an element with a mass, m, and a characteristic length, r, vibrating in the liquid with a frequency $\nu = \omega/2\pi$ and an amplitude, a. The energy of the element will be, $w = 1/2\ m\omega^2a^2$. From Stokes law considerations, the retarding frictional force will be,

$$F_d = \kappa 6\pi\mu r\omega a \tag{11}$$

in which $\kappa = 1$ for a sphere of radius r and μ is taken as the viscosity of water.

The power lost to viscous friction will be $dw/dt = F_d\omega a$, and the time constant (or lifetime) will be

$$\tau = \frac{w}{dw/dt} = \frac{m}{12\pi\kappa\mu r} \tag{12}$$

We can establish a benchmark numerical value by taking the element as a sphere in which $m = \rho(4\pi/3)r^3$ and $\kappa = 1$. Then

$$\tau = \frac{1}{\Gamma_a} = \frac{\rho}{9\mu}\,r^2 = 1.6 \times 10^5 r^2 \tag{13}$$

in which the numerical value follows from taking ρ and μ as the density and viscosity of water, and r is measured in meters.

The oscillatory motion of near-cylindrical elements in the direction of their axis generates resistive forces. For a cylinder of radius (r), length (L), oscillating longitudinally with a frequency $\nu = \omega/2\pi$, and amplitude (a), the retarding force can be expressed approximately as

$$F_d \approx \frac{2\pi\mu L\omega a}{\ln(c/\omega r)} \quad \text{for} \quad r < \frac{c}{\omega} < L \tag{14}$$

in which c is the velocity of sound in the liquid medium.

Taking the mass of the cylinder as $\pi r^2L\rho$, in which ρ is the density of the cylindrical material,

$$\tau = \frac{1}{\Gamma_a} \approx \frac{\pi r^2L\rho(\omega a)^2/2}{2\pi\mu L(\omega a)^2/\ln(c/\omega r)} = \frac{r^2\rho\,\ln(c/\omega r)}{4\mu}. \tag{15}$$

For such typical values as $r = 2 \times 10^{-9}$ m, and ρ and μ taken as that of water, $\tau = \tau_a = 1/\Gamma_a \approx 10^{-11}$ s and such

systems will generally be critically damped at microwave frequencies.

Under some circumstances, a system that oscillates with mechanical movement will lose energy through the inertial forces exerted in moving the surrounding liquid and thus generating sound waves. Such inertial effects can only be expected for systems described by Reynold's numbers, $Re = \rho r v/\mu > 1$ in which r and v are characteristic lengths and velocities of the object. For most biological systems oscillating at microwave frequencies, $Re \ll 1$ and acoustic energy losses will not be important.

LONGITUDINAL VIBRATIONS IN CYLINDRICAL SYSTEMS

DNA

For the candidate resonances that we consider, the elements moving in their aqueous biological elements will lose energy to the surrounding liquid through viscous impedance. "Organ pipe" standing sound waves propagated longitudinally along cylindrical structures, such as DNA, seemed likely to have the longest relaxation times for elements in water. However, Dorfman and Van Zandt (1983) showed that with plausible assumptions on the character of the viscosity, such a resonance (and a resonance in any other mode) would be over-damped.

However, in the course of considering resonances in the DNA microwave absorption spectra reported by Edwards et al. (1984) and interpreted as such sound waves, Van Zandt (1986) revisited the subject and concluded that relaxation times for such vibrations might be as long as $\tau_a \approx 5$ ns, a value taken from the narrow widths, $\Gamma_a \approx 200$ MHz, of his calculated resonances. Even as the theoretical widths were an order of magnitude smaller than the experimental widths, the calculated value of the relaxation time was an order of magnitude longer than the times suggested by the data that the authors (Edwards et al., 1984) estimated as $\tau_a < 500$ ps.

Following this previous work, I consider specifically the DNA strand of 5480 base pairs with a mass of $\sim 10^6$ Daltons and a length, s, of ~ 3.3 μm. I assume coupling to the field through single charges $q = e$ at each end thus a permanent dipole moment of 5.3×10^{-25} Cm.

For a given value of the relaxation time and the corresponding absorption width, the maximal resonant cross-section, as calculated from Eqs. 4 and 10, is independent of frequency.

$$\sigma_{max} = \frac{8q^2}{\epsilon_0 mc\Gamma_a} \quad \text{and} \quad \Delta w = \frac{8Iq^2}{\epsilon_0 mc\Gamma_z^2} \qquad (16)$$

For $\tau_a = 1/\Gamma_a = 5$ ns, $q = e$, and an incident microwave power level $I = 100$ W/m^2 (10 mW/cm^2), about the recommended regulatory limit for general human exposure (IEEE, 1991), the maximal energy stored by the resonant system would be $\Delta w = 1.15 \times 10^{-29}$ J $= 2.8 \times 10^{-9}$ kT. Thus, the absorption of microwave radiation by such resonances cannot be expected to affect biology even if the resonant modes are not so strongly damped. Indeed, the stored energy can only be large if the state is very long lived and, hence, very narrow. For $\Delta w > kT$, when the incident power density is $I = 100$ W/m^{2}m then $\Gamma < 10$ kHz.

Although the value $q = e$, chosen to describe the oscillating dipole moment already implies a very large permanent dipole moment, if the oscillating charge were greater than $2 \times 10^4 e$, the radiative absorption from the canonical incident microwave power density would be increased to detectable levels if the relaxation time is as large as 5 ns. But so large a charge leads to a moment that seems far outside of our understanding of DNA or any other molecule.

The conclusion that there can be no microwave resonances in DNA in water is in accord with the results of measurements in three different laboratories (Gabriel et al., 1987; Foster et al., 1987) using techniques designed to detect resonances with amplitudes less than 1/20th of that reported by Edwards et al. (1984).

Voltage-gated ion channels

The voltage-gated ion channels, important in the generation and propagation of action pulses in neurons, are of special interest here because the well-established dipole moments of the protein channel play an essential role in neurophysiology. Hence, any significant effect of the interaction of microwaves with these elements through their dipole moments can be expected to translate directly into physiological effects.

Most varieties of the protein channels that pass cations through the cell membrane upon changes in the membrane potential appear to be constructed of four similar segments, conventionally labeled I, II, III, and IV, each of which crosses the membrane. Each segment seems to be divided into six sectors, S1, S2, ... S6 (Hille, 1992; Shepherd, 1994). The segments, which seem to act nearly independently of each other, appear to change their configuration from a closed state to an open state when the potential difference across the membrane changes from the resting polarization potential, typically near $V_m = -70$ mV, to near zero. The channel is open to ion transmission when four (or, perhaps, three) segments are in the open state.

The change in the segment configuration appears to result from the effects of the transmembrane field on dipole moments held in the S4, "voltage-sensing," sector of each segment. When the channel is depolarized a "gating-current" flows with a total charge transfer across the membrane of approximately $Q = 6e$. The occupations of the open and closed configurations, as estimated from statistical mechanics, are consistent with the view that the energy difference between the open and closed channel configurations is approximately equal to QV_m. Thus, we tentatively describe dipole moment of each of the four S4 sectors as $d_0 =$

$Qd_{mem}/4 = 1.5ed_{mem}$ in which $d_{mem} \approx 7$ nm is the membrane thickness.

The mass of each segment appears to be near 75 kD, and we take the effective moving mass as that of the S4 sector at $m \approx 15$ kD. (If the moving mass is larger, the absorbed energy will be smaller.)

In each cell or active sector of a cell (e.g., the nodes of Ranvier) there are very many channels that act together. Moreover, the dynamics is complicated by positive feedback effects such that the opening of channels admits ions that change the membrane potential in a manner that further increase the channel open probability. However, for standard Hodgkins-Huxley Na channels (Hodgkins and Huxley, 1952), we know that there is an effective threshold of approximately $\Delta V_m \approx 6$ mV for the cascade that results in neuron spike generation (Koch, 1999). Thus we can take $Q\Delta V_m \approx kT/3$ as a rough measure of the energy threshold, applied to one channel, for significant effects.

Using the same arguments as for the DNA resonance and thus Eq. 16, we find that for $I = 100$ W/m^2, and $\Delta w = kT/3$, $\Gamma < 225$ kHz. Estimating $\Gamma_a = 1/\tau \approx 10$ GHz from Eq. 13, we see that, despite the large uncertainties in the estimates, microwaves of moderate intensity cannot be expected to effect neurophysiology through resonant interaction of the S4 voltage-sensor sectors.

Resonances in microtubules

Pokorny and colleagues have argued that microtubules in cells will exhibit sharp mechanical resonances at megahertz frequencies (Pokorny et al., 1997). However, K. R. Foster and J. W. Baish (personal communication) have shown that the resonances would be strongly damped by viscous processes.

COHERENT PROCESSES

Frölich (1968) has emphasized the possible importance of the oscillations of systems where many dipole moments act coherently. In particular, he has suggested that such oscillations may be generated in the cell membranes that may affect biology. Following the specific example he describes, we consider such a membrane normal to the electric field where internal and external electric charges that account for the normal $V_{mem} \approx 60$ mV polarization potential across the membrane form dipole moments. The alternating electric field will induce alternating compressive and expansive (tension) forces on the membrane through their action on the charges that bound the membrane.

We can expect a resonance frequency such that $\nu_{res} = v_{mem}/d_{mem} \approx 2 \times 10^{11}$ Hz, and we estimate v_{mem}, the speed of sound in the membrane, as 1500 m/s, the speed of sound in water. The wavelength is then $\lambda = 1.5$ mm.

Taking the specific capacity of the membrane as $c_m = 0.01$ F/m^2 (1 μF/cm^2) and the resting potential as $V_m = -60$ mV, the charge density $Q = V_m c_m \approx 7 \times 10^{-4}$ C/m^2. Thus the charge on a characteristic sector of membrane with an area, $A = L^2 = 10^{-10}$ m^2 will be $q \approx 7 \times 10^{-14}$ C.

We can estimate the mass of the sector as $m = L^2 d_{mem}\rho \approx 7 \times 10^{-16}$ kg by taking the membrane element as an area L^2 in which $L = 10$ μm, a thickness as $d_{mem} = 7$ nm, and $\rho = 1000$ kg/m^3, the density of water.

With these values we find, using Eq. 9,

$$\Gamma_s = \frac{q^2\omega^2}{6\pi\epsilon_0(m/4)c^3} \approx 10^{-5}\ \mathrm{s}^{-1} \tag{17}$$

Because the whole membrane does not move in a compression-rarefaction mode, the effective mass is reduced by a factor of 4, hence the quantity $(m/4)$ in the relation.

We estimate a relevant Reynold's number as $Re = \rho L\omega a/\mu \approx 2 \times 10^4 \times a$ in which a is the amplitude in nm. If a is large, and $Re \gg 1$, the vibrating membrane will displace fluid inertially generating acoustic waves.

For a vibrational amplitude a, the energy of membrane vibration will be, $w \approx (1/8)m(\omega a)^2$. The corresponding acoustic power density will be $p = c_m \times 2\rho(\omega a)^2$ in which $c_m \approx 1500$ m/s is the velocity of sound in the liquid bordering the membrane and the factor "2" takes into account the two sides of the membrane.

The power lost by the membrane, radiating in two directions, will then be, $dw/dt = L^2 p = c_m \rho L^2(\omega a)^2$ and the lifetime of the state will be

$$\tau_a = \frac{1}{\Gamma_a} = \frac{w}{dw/dt} = \frac{(1/8)\rho_m L^2 d_{mem}(\omega a)^2}{c_m L^2 \rho_m (\omega a)^2}$$

$$\approx \frac{d_{mem}}{8c_m} \approx 6 \times 10^{-13}\ \mathrm{s} \tag{18}$$

taking $\rho_m \approx \rho$

Because this life time is less than the radiation period, $\tau_a = 1/\nu \approx 5 \times 10^{-12}$ s, the membrane vibrating in water will be so over-damped that we can expect no resonance.

Taking these values of Γ_s and Γ_a, the incident intensity again as $I = 100$ W/m^2, and a frequency $\nu = 2 \times 10^{11}$ Hz from Eq. 4, the maximal energy deposition will be

$$\Delta w = 2 \times 10^{-30}\ \mathrm{J} \quad \text{and} \quad \frac{\Delta w}{kT} = 4.8 \times 10^{-10} \tag{19}$$

Hence, even if the dissipation were reduced by a factor of 10^4 and the resonance were not overly damped, the energy deposition would still be much less than kT and too small to affect biology.

From Eq. 5, we can express the limit for biological potency in terms of a maximal width (and minimal damp-

ing). If the oscillation energy is to be greater than kT, the resonance width $\Gamma < 1.4$ MHz.

If the amplitudes are small and $Re < 1$, inertial effects will be negligible and the vibration will be damped viscously. Here we estimate the retarding viscous force following the Stokes recipe for a sphere as $F \approx 6\pi\mu Lv$ in which $v = \omega s$. The dissipated power will then be, $dw/dt = Fv = 6\pi\mu Lv^2$. The lifetime will then be

$$\tau = \frac{w}{dw/dt} = \frac{(1/8)\rho L^2 d_{\text{mem}} v^2}{6\pi\mu Lv^2} = \frac{\rho L d_{\text{mem}}}{48\pi\mu} \approx 4 \times 10^{-10}\ \text{s} \tag{20}$$

and, again, the system is heavily damped and no resonance effects can be expected.

MAGNETOSOME RESONANCES

Kirschvink (1996) has suggested that the resonant interaction of microwaves with magnetosomes may affect biology through ultrasound emitted by the magnetosomes. Energy absorbed by the domains through the coupling of their magnetic moment with the radiative field would be presumed to generate such sound through the known magnetoacoustic effect.

At the resonant frequency, the external AC field generates a precession in the electrons that contribute to the ferrimagnetism. For an electron that is not strongly coupled magnetically to its nearby environment that angular frequency is simply, $\omega = Be/m = 1.76 \times 10^{11} \times B_{\text{ext}}$, in which e and m are the charge and mass of the electron and B_{ext} is the external field imposed on the material. However, in ferromagnetic and ferrimagnetic materials, that frequency is strongly modified by dipolar interactions with near neighbors and depends on both the external field and internal demagnetizing fields present in the magnetic domains. In turn, those fields depend strongly on the shape of the domain with respect to the crystal structure (Kittel, 1949; Kittel and Abrahams, 1953).

Radiative width

The moment of a single domain magnetosome of volume, v, is $m_0 = H'v$ in which $H' = 4.8 \times 10^5$ A/m. Then, for a cubical magnetosome $d_{\text{m}} = 50$ nm on a side, $m_0 = 6 \times 10^{-17}$ Am^2, which we take as a typical value for a magnetosome. For such a perfect cube, the resonance frequency, ν_{r}, will be ~1.1 GHz (Kittel, 1949). Shape anisotropies add as much as 8 GHz to this; for our calculations we chose a canonical frequency of $\nu_{\text{r}} = 2$ GHz.

The power p radiated by a such a magnetic dipole moment oscillating at a frequency of $\omega = 2\pi\nu_{\text{r}} = 1.26 \times 10^{10}$ rad/s is that expressed by Eq. 8 with the substitution, $d_0 \rightarrow m_0/c$, $p \approx 1.1 \times 10^{-25}$ W.

The frequency is that of the precession of the electrons in the demagnetizing field (Van Vleck, 1951). Taking that precession frequency as $\omega_{\text{e}} = Be/m = 1.76 \times 10^{11} \times B$ rad/s, we have $B = 0.0714$ T and a characteristic alignment energy, $w = B\mu = 4.3 \times 10^{-18}$ J. From this, we estimate $\Gamma_{\text{s}} \approx P/w = 2.6 \times 10^{-8}\ \text{s}^{-1}$.

Absorption width

The absorption width, very much greater than the radiative width, is not as well known. For the purpose of our illustrative calculations, we take the estimate of Abrahams (Kittel and Abrahams, 1953) that the lifetime of ferrimagnetic resonance is likely to be $\tau \approx 7 \times 10^{-7}$ s and then $\Gamma_{\text{a}} \approx 1/\tau = 1.4 \times 10^6\ \text{s}^{-1}$.

Absorbed power and stored energy

From Eq. 4, the power absorbed by the magnetosome at resonance in a radiative field of 100 W/m^2 power density is, $p = 1.6 \times 10^{-13}$ W and the stored energy will be $\Delta w = P/\Gamma = 1.15 \times 10^{-19}$ J ≈ 25 kT. If this energy were entirely manifest as heat, the temperature of the magnetosome would be increased by $\Delta T \approx 5 \times 10^{-4}$ °C, which is, of course, biologically negligible. If all of the energy were engaged in acoustic vibrations of the element, we can estimate the velocity of motion of the surface as $v \approx (2w/m)^{1/2} \approx 0.75$ m/s. Writing Reynold's number in the surrounding fluid as $Re = \rho d_{\text{m}} v/\mu \approx 0.05$, it is clear that any vibration will dispense energy in viscous resistance rather than the mass movement of acoustic radiation.

CONCLUSIONS

There are both theoretical conjectures (Frölich, 1968; Van Zandt, 1986) and experimental results (Edwards et al., 1984; Grundler and Keilman, 1983) that suggest that low intensity microwaves fluxes might affect biology through the excitation of elastic resonances in biological systems. We extend analyses that suggest that the damping of the vibratory motion by biological fluids severely restrict such possibilities (Van Zandt, 1986) by showing that typical systems will not be coupled to the electromagnetic fields with sufficient strength to allow significant energy transfers although the damping constraint be somewhat relaxed.

REFERENCES

Adair, R. K. 1995. Effects of weak high-frequency electromagnetic fields on biological systems. *In* Radiofrequency Radiation Standards. B. J. Klauenberg, M. Grandolfo, and D. N. Erwin, editors. Plenum Publishing Corp., New York. 207–222.

Blatt, J. M., and V. F. Weiskopf. 1952. Theoretical Nuclear Physics. Wiley, New York.

Dorfman, B. H., and L. L. Van Zandt. 1983. *Biopolymers.* 22: 2639.

Edwards, G. S., C. C. Davis, J. D. Saffer, and M. L. Swicord. 1984. Resonant absorption of DNA molecules. *Phys. Rev. Lett.* 53:1284–1287.

Foster, K. R., B. R. Epstein, and M. A. Gealt. 1987. "Resonances" in the dielectric absorption of DNA? *Biophys. J.* 52:421–425.

Frölich, H. 1968. Long range coherence and energy storage in biological systems. *Int. J. Quantum Chem.* 2:641–649.

Gabriel, C., E. H. Grant, R. Tata, P. R. Brown, B. Gestblom, and E. Noreland. 1987. Microwave absorption in aqueous solutions of DNA. *Nature.* 328:145–146.

Grundler, W., and F. Keilman. 1983. Sharp resonances in yeast growth from non-thermal sensitivity to microwaves. *Phys. Rev. Lett.* 51: 1214–1216.

Hille, B. 1992. Channels of Excitable Membranes, Second Edition. Sinnauer Associates, Sunderland, MA.

Hodgkins, A. L., and A. F. Huxley. 1952. A quantitative description of membrane current and its application to conduction and excitation in nerve. *J. Physiol. London.* 117:500–544.

IEEE C95.1-1991. 1991. IEEE Press, Piscataway, NJ.

Kirschvink, J. L. 1996. Microwave absorption by magnetite: a possible mechanism for coupling nonthermal levels of radiation to biological systems. *Bioelectromagnetics.* 17:187–194.

Kittel, C. 1949. On the gyromagnetic ratio and spectroscopic splitting factor of ferromagnetic substances. *Phys. Rev.* 76:743–748.

Kittel, C., and E. Abrahams. 1953. Relaxation processes in ferrimagnetic substances. *Rev. Mod. Phys.* 25:743.

Koch, C. 1999. Biophysics of Computation. Oxford, NY. 153.

Maret, G., R. Oldenbourg, G. Winterling, and K. Dransfeld. 1979. Velocity of high frequency sound waves in oriented DNA fibers and films determined by Brillouin scattering. *Colloid. Polym. Sci.* 257:1017–1020.

Pokorny, J., F. Jelenek, V. Trkval, I. Lamprecht, and R. Holtzel. 1997. Vibrations in microtubules. *J. Biol. Phys.* 48:261–266.

Shepherd, G. M. 1994. Neurobiology. Oxford, NY.

Stewart, W. 2000. Mobile Phones and Health, Independent Expert Group on Mobile Phones. National Radiological Protection Board, Chilton, Didcot.

Van Vleck, J. H. 1951. Ferrimagnetic resonance. *Physica.* 17:234–252.

Van Zandt, L. L. 1981. Damping of DNA vibration modes by viscous solvents. *Int. J. Quantum Chem., Symp.* 8:271–276.

Van Zandt, L. L. 1986. Resonant microwave absorption by dissolved DNA. *Phys. Rev. Lett.* 57:2085–2087.