

UNCONVENTIONAL APPROACH TO BIOLOGICAL EFFECTS OF EMF

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Abstract. The traditional way to describe the interactions in a system is to put the charged particles in the center of the formalism; the particles are excited and de-excited and in these processes radiation is absorbed and emitted, respectively. Here we put the electromagnetic fields in the center. The particles' role is to contribute to the dielectric function and magnetic permeability of the system components. The interactions are described in terms of so-called electromagnetic-normal-modes of the system. The formalism complements the traditional one and leads to a broader understanding of, and feeling for, what goes on inside a biological system.

Keywords: electromagnetic-normal-modes; dispersion forces; van-der-Waals forces; Casimir forces; surface tension; biocompatibility

1. Introduction

Not counting gravitational effects, basically all interactions we experience are of electromagnetic origin. Traditionally the formalism is centered around the particles; electrons are excited and de-excited inside atoms; partly charged atoms are displaced from their equilibrium positions in polar semiconductors;

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atoms or molecular parts are set in vibration inside molecules; mobile ions are set in motion in electrolytes; polar molecules, like the water molecule, are set in rotation. In these processes radiation is absorbed or emitted. All these processes involve the interaction between matter (the particles) and radiation (the fields). An alternative approach is to put the radiation, or electromagnetic fields, in the center. This is the approach we take here.

The electromagnetic interactions can be expressed in terms of the electromagnetic-normal-modes of the system—solutions to Maxwell's equations in absence of external sources. Some examples where this approach has been demonstrated¹ to give results equivalent to those from the traditional approach are: the exchange- and correlation-energy in a metal; the polaron energy in a polar semiconductor or ionic insulator; the van-der-Waals² and Casimir^{3,4} interactions between atoms, molecules, mesoscopic and macroscopic objects.

At low temperature and in absence of a radiation field the interactions are in terms of the zero-point energy of the modes, or expressed in another way they are due to vacuum fluctuations. When the system changes these zero-point energies change and forces arise; the normal modes change when the conduction-electrons are brought together to form the metal, and the change in zero-point energy is the exchange- and correlation-energy; when two systems, one with a single electron and one with optical phonons, is combined into one the normal modes change and the change in zero-point energy of the modes is the polaron energy; when two atoms are moved relative each other the normal modes and their zero-point energies change, which results in a force — the van-der-Waals and Casimir force.

At finite temperature, or in the presence of radiation, the modes get populated. Now, not only the zero-point energy contributes to the energies and forces but also the energy of the real modes. Thus the energies stored in the system and the forces between objects are modified. In a biological system the objects may be cells or nearby interfaces separating regions of different tissue-type. The surface tension or surface energy of interfaces may change. This may modify the mechanical properties of the tissue and might also influence the ability of the interfaces to attract and harbor impurities. As an example it might influence, in a negative way, the biocompatibility of implants.

2. Finding the normal modes

As we said in the introduction, basically all interactions we experience are of electromagnetic origin. We may see objects; we experience they are different colors, some are transparent and some are opaque. That we see objects at all is

really a stroke of luck. If we study the volume taken up by the particles making up matter—the electrons, protons, and neutrons—we find that it is a negligible part of the total volume. This is why neutrinos pass through the earth all the time without even noticing that the earth exists. The reason we see things is that the photons interact with matter, or expressed in another way there are normal modes filling the “empty” space between the particles.

We drive currents through wires in electronic equipment and in computers; we transmit radio-waves through the atmosphere between transmitting and receiving antennas for radio- and TV-broadcasting; we may use resistive heating or inductive heating to cook our food on the stove or use microwave radiation to heat the food in the microwave ovens; our heart rhythm is determined by a steady flow of electromagnetic signals. We could go on and on just to list the electromagnetic effects we experience and utilize in different techniques.

What is most remarkable is that all these very different effects are described by the same four equations—the Maxwell equations:

$$\nabla \cdot \mathbf{D} = 4\pi\rho;$$

$$\nabla \cdot \mathbf{B} = 0;$$

$$\nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = 0;$$

$$\nabla \times \mathbf{H} - \frac{1}{c} \frac{\partial \mathbf{D}}{\partial t} = \frac{4\pi}{c} \mathbf{J}.$$

These are equations for the four fields \mathbf{E} , \mathbf{D} , \mathbf{B} , and \mathbf{H} . In the case of time dependent fields the last two equations lead to a coupling between the electric and magnetic fields. The sources, the charge- and current-densities, for the fields appear on the right-hand-side of the 1st and 4th equation, respectively. The \mathbf{E} - and \mathbf{B} -fields are the fundamental fields and the \mathbf{D} - and \mathbf{H} -fields are auxiliary fields, or help-fields. The auxiliary fields are related to the fundamental fields through the so-called constitutive relations,

$$\mathbf{D} = \tilde{\epsilon}\mathbf{E};$$

$$\mathbf{B} = \tilde{\mu}\mathbf{H},$$

where the functions $\tilde{\epsilon}$, and $\tilde{\mu}$ are the dielectric function and the magnetic permeability of the medium, respectively. The charged particles in the system may be grouped in different ways: one way is to let only bound charges contribute to the induced charge- and current-densities and let all mobile carriers, i.e. conduction electrons and mobile ions, be lumped together with the external charges that contribute to the sources; one way is to let the mobile

charges contribute to the induced charge- and current-densities in the medium and not contribute to the sources. How one groups the charges is just a matter of bookkeeping. The tilde over the dielectric function and magnetic permeability indicates that we let the mobile carriers, i.e. conduction electrons and mobile ions, contribute to the dielectric and magnetic response of the medium. This bookkeeping means that the sources in Maxwell's equations are the external densities. We will first study the solutions to Maxwell's equations inside a piece of material, far away from the outer surfaces and from any interfaces, i.e. we limit the treatment to the bulk.

2.1. BULK MODES

The solutions to Maxwell's equations and the constitutive relations in the bulk are

$$\mathbf{E}_\perp(\mathbf{q}, \omega) = i \frac{4\pi\omega\tilde{\mu}_\perp(\mathbf{q}, \omega)\mathbf{J}_\perp^{ext}(\mathbf{q}, \omega)}{(cq)^2 - \omega^2\tilde{\mu}_\perp(\mathbf{q}, \omega)\tilde{\epsilon}_\perp(\mathbf{q}, \omega)};$$

$$\mathbf{H}_\perp(\mathbf{q}, \omega) = i \frac{4\pi c\mathbf{q} \times \mathbf{J}_\perp^{ext}(\mathbf{q}, \omega)}{(cq)^2 - \omega^2\tilde{\mu}_\perp(\mathbf{q}, \omega)\tilde{\epsilon}_\perp(\mathbf{q}, \omega)};$$

$$E_L(\mathbf{q}, \omega) = \frac{-i4\pi\rho^{ext}(\mathbf{q}, \omega)}{q\tilde{\epsilon}_L(\mathbf{q}, \omega)};$$

$$\tilde{\mu}_L(\mathbf{q}, \omega)qH_L(\mathbf{q}, \omega) = 0.$$

The fields in the two first equations are transverse, i.e., the fields are perpendicular to the propagation direction, defined by the wave-vector \mathbf{q} . The fields in the two last equations are longitudinal, i.e., the fields are parallel to \mathbf{q} . We have here been a little more stringent and added subscripts to the dielectric and magnetic response functions indicating that the response to a transverse field may be different from that to a longitudinal field.

We see that we can have solutions to Maxwell's equations in absence of external sources if any of the following relations hold:

$$\omega^2 = \frac{(cq)^2}{\tilde{\mu}_\perp(\mathbf{q}, \omega)\tilde{\epsilon}_\perp(\mathbf{q}, \omega)};$$

$$\begin{aligned}\tilde{\epsilon}_L(\mathbf{q}, \omega) &= 0; \\ \tilde{\mu}_L(\mathbf{q}, \omega) &= 0.\end{aligned}$$

These relations determine the dispersion curves, ω as a function of \mathbf{q} , for the electromagnetic-bulk-normal-modes. The first gives transverse modes and the two last give longitudinal modes. If we had the proper sources with the proper combination of frequency and momentum the field would diverge. This is in analogy with mechanical systems when we hit a resonance frequency. We can visualize the normal modes as resonances in the electromagnetic system in analogy with resonances in mechanical systems. We realize that these modes are very easy to excite.

Next we will study what happens at a surface or at an interface between two media.

2.2. SURFACE MODES

At the interface between two media, 1 and 2 , there are other solutions to Maxwell's equations, solutions where the fields are localized to the interface. These are obtained from solving Maxwell's equations on the two sides of the interface and using the standard boundary conditions for the fields at the interface, i.e. that the parallel components of the \mathbf{E} - and \mathbf{H} -fields and the perpendicular components of the \mathbf{D} - and \mathbf{B} -fields are continuous across the interface.

The resulting condition for having a mode at an interface between two non-magnetic media is

$$\sqrt{k^2 - \tilde{\epsilon}_1(\omega)(\omega/c)^2} \tilde{\epsilon}_2(\omega) = -\sqrt{k^2 - \tilde{\epsilon}_2(\omega)(\omega/c)^2} \tilde{\epsilon}_1(\omega),$$

where \mathbf{k} is a two-dimensional wave vector in the plane of the interface. Note that we have neglected the wave-vector dependence of the dielectric functions here, i.e. neglected spatial dispersion. Inclusion of spatial dispersion would make the treatment much more involved and it would in most cases have very little effect on the results⁵. The modes we are discussing now are so-called surface modes. There are modes associated with all types of excitation in the media on the two sides of an interface: electronic excitations within atoms or in solids; vibrational excitations in molecules or in solids; rotational excitations of molecules in solids, liquids or gases; excitations of mobile ions. These excitations show up in the dielectric functions and magnetic permeabilities of the media. All objects in the universe have fields localized to their outer surfaces and to their interior interfaces and this has important consequences.

3. Energy of the normal modes

A mode means the presence of electromagnetic fields. The presence of electromagnetic fields means energy. The energy density in an electromagnetic field is

$$u = \frac{1}{8\pi} (\mathbf{D} \cdot \mathbf{E} + \mathbf{H} \cdot \mathbf{B}).$$

Energy is stored in the bulk and at interfaces. If the system changes, the modes and the energies change. The energy stored at an interface, the surface energy, or surface tension, affects mechanical properties; it gives rise to capillary forces in hollow structures; it affects biocompatibility; it gives rise to dispersion forces between cells, between molecules and cells and between nearby interfaces.

The energy stored in the modes is for the bulk modes equal to

$$E = \sum_{\mathbf{q}} \sigma \hbar \omega_{\mathbf{q}} \left(n_{\mathbf{q}} + \frac{1}{2} \right),$$

for the surface modes it is

$$E = \sum_{\mathbf{k}} \sigma \hbar \omega_{\mathbf{k}} \left(n_{\mathbf{k}} + \frac{1}{2} \right),$$

and for general modes it can be written as

$$E = \sum_i \sigma \hbar \omega_i \left(n_i + \frac{1}{2} \right),$$

where the summation runs over the modes.

To be noted is that, in the approach we have taken, the quantum mechanics is in these energy relations and in the dielectric functions and the magnetic permeabilities. When solving the problem we deal with classical fields. Thus this formalism is much simpler than the traditional one. The frequencies in the energy relations are the solutions to the condition giving the mode. The term $(1/2)\hbar\omega_i$ is a pure quantum mechanical effect and is the zero-point energy, the energy of vacuum fluctuations. The n_i is the occupation number of the mode. These modes are so-called mass-less bosons.

If the system is in thermal equilibrium these occupation numbers are the distribution functions for mass-less bosons. At zero temperature the occupation numbers are zero and only the zero-point energy remains. In the presence of non-thermal radiation the occupation numbers take on other values.

4. Examples of modes

Let us now study some examples of different mode-types. The first example is in the infrared range in the bulk of a polar semiconductor. Here the active excitation mechanism is optical phonons. The resulting dispersion curves for the normal modes are shown in Fig. 1.

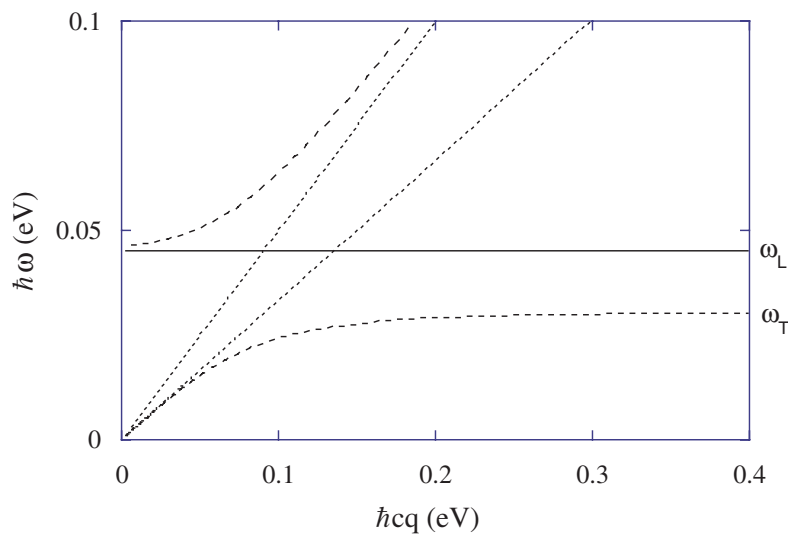


Figure 1: Transverse (dashed curves) and longitudinal (solid curve) bulk modes in a polar semiconductor. The dotted curves are the asymptotes for the two transverse branches.

There is one branch of longitudinal modes. There are two branches of transverse modes, separated by a gap. This transverse mode is the refracted waves we get as a result when an external plane wave impinges on the surface of the semiconductor. Note that there is a gap between the two branches and an impinging wave with frequency in this gap will be totally reflected; there will be no refracted wave in the gap region.

It is in this gap that we find surface modes. This is illustrated in Fig. 2.

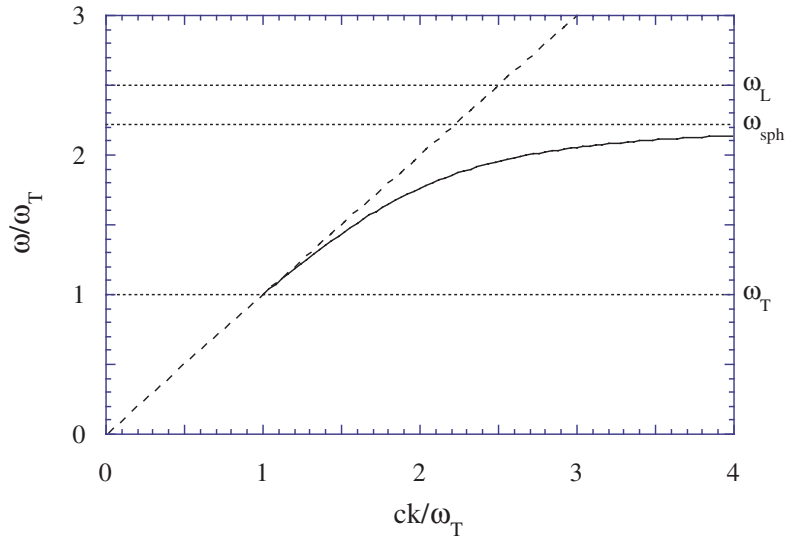


Figure 2: The dispersion curve (solid curve) for the surface mode at the surface of the polar semiconductor, discussed in Fig. 1. The dashed curve is the dispersion curve for light in vacuum. The dotted, horizontal lines are the frequencies for the longitudinal phonon, the surface phonon, and the transverse phonon, respectively, counted from above.

The dispersion curve for the surface modes is the frequency as function of the two-dimensional wave-vector in the plane of the surface. These surface modes are surface phonons.

As a final example we show in Fig. 3 the six normal modes for two interacting Lithium atoms as function of separation between the atoms.

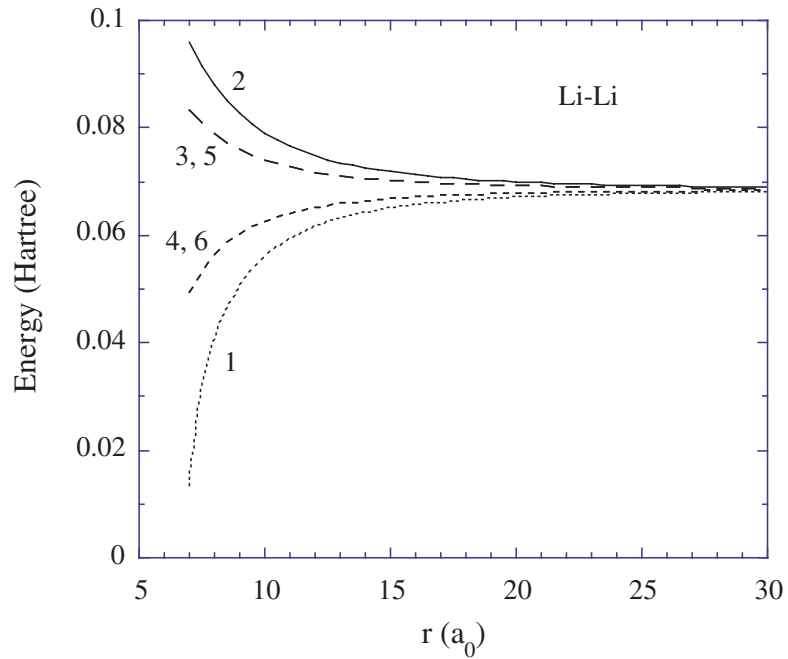


Figure 3: The energy as function of separation of the six normal modes for a system of two interacting Lithium atoms.

The resulting dispersion force is

$$F = \sigma \sum_i \left\{ n_i \omega_i(r) + 1/2 \right\} - \hbar \partial \omega_i(r) / \partial r .$$

Modes number 1,4 and 6 are attractive, while modes number 2,3 and 5 are repulsive. When the occupation numbers are zero the overall force is attractive. The result is shown in Fig. 4.

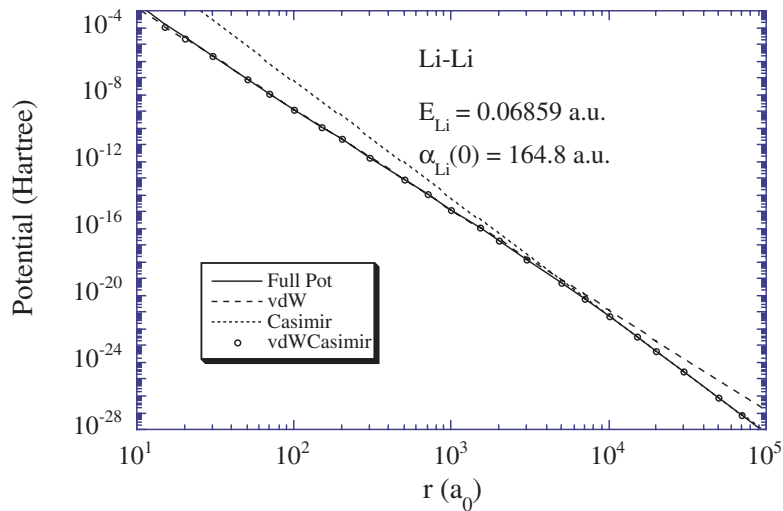


Figure 4: The dispersion force between two Lithium atoms as function of separation.

For intermediate separations the force is the van-der-Waals force and at larger separations it turns into the Casimir force. These two forces are shown as dotted asymptotes in the figure. The circles are our obtained results for the potential. The solid curve is the result from a full quantum mechanical calculation⁶ including also higher order multi-pole contributions.

One may manipulate the force—make it stronger, weaker or even repulsive by changing the occupation numbers. This may be done either by thermal radiation or by other radiation. In absence of radiation, even thermal radiation ($T = 0$), the occupation numbers are zero. Still energy is stored in the modes—the zero-point energy. In presence of radiation the modes get populated and the energies and forces get modified.

5. How may the modes be affected by EMF?

Now, we may speculate on what might happen in a biological system exposed to an electromagnetic field. The dispersion forces between objects and between nearby interfaces might be altered; the forces between blood cells; the attachment of molecules, like viruses, to cells might be affected; pH might change.

Blood is a colloid and in colloids there usually is an intricate balance between repulsive and attractive forces between the particles in the dispersed phase. If the attractive part of the force is changed this balance might be lost. A typical potential between colloidal particles is shown in Fig. 5.

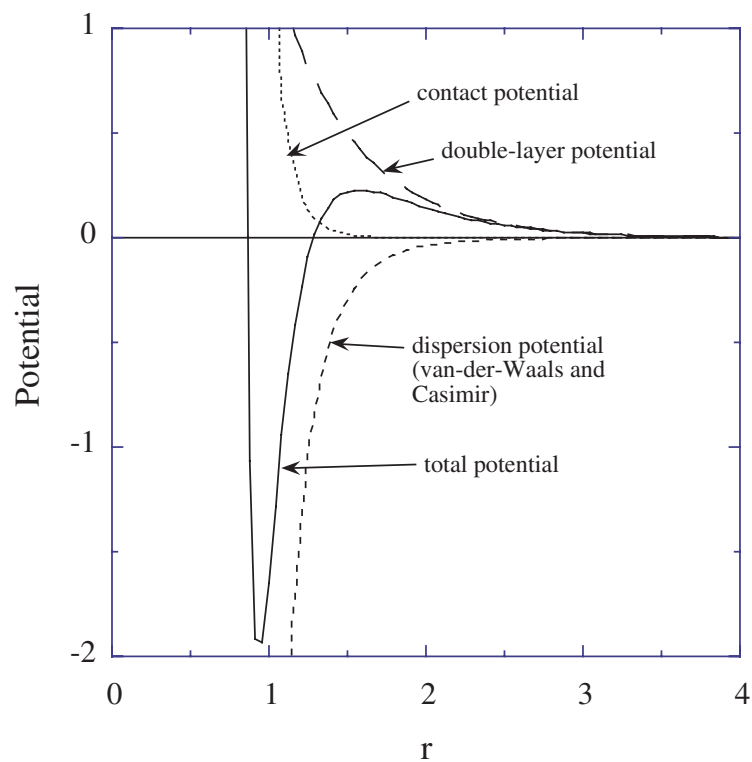


Figure 5: A typical potential between two colloidal particles consists of three contributions: one very short range, repulsive contact-potential (dotted curve); one short-range, repulsive so-called double-layer potential (short-dashed curve); one long-range, attractive van-der-Waals and Casimir potential (long-dashed curve). The resulting potential (solid curve) has two minima separated by a barrier—one shallow outer minimum and one inner deep minimum.

The typical resulting potential has two minima separated by a barrier. If the particles are trapped in the outer, shallow minimum they are easily released again; the process is reversible. If they are trapped in the inner, deep minimum,

the process may be irreversible; reconstruction or chemical bonding may occur and the stability of the colloid gets lost.

The red blood cells are not spherical but look more like in Fig. 6.

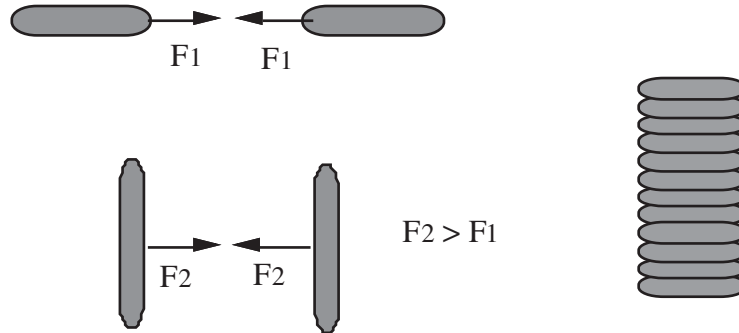


Figure 6: Orientation dependent forces between two red blood cells may favor “coin-stack-formation.”

The attractive dispersion forces are stronger if the cells have their flat sides facing each other. An enhancement of the dispersion forces could lead to enhanced occurrence of “coin stacks”.

When the earth was young the water in the sea had much lower salt concentration than it has nowadays. Rain brought salt to the sea and the concentration gradually increased. Our ancestors left the sea to live on land when the salt concentration reached the limit of approximately 0.15 molar, which is the biological, or physiological, salt concentration. This happens to be close to the concentration where the barrier between air-bubbles is not big enough to prevent two bubbles to coalesce⁷. One may speculate in if this was the reason for leaving the sea. This sensitive balance preventing the bubbles to coalesce might be broken due to the presence of an electromagnetic field.

One requirement for biocompatibility of a medical implant, like a dental implant or a pacemaker, is that the surface energy at the interface between the implant and surrounding tissue is low. This means that the electromagnetic fields stored in the surface modes are weak. If the surface energy increases there are stronger electromagnetic fields at the interface. There is a tendency that polarizable entities, like foreign atoms or molecules are attracted by the interface. They screen the fields and this lowers the energy. This leads to plaque formation at the interface. The effect that interfaces attract impurities is well known in other areas of science. Compare the floatation technique used in water purification and in gold mining.

In order for an important dispersion force to occur between two objects in an ambient there has to be a dielectric contrast between the objects and the ambient medium. For an electromagnetic field to have an effect on this force the frequency of the field has to be in a range where the contrast is big.

Note that the possible effects we have suggested above are just pure speculations. We have no supporting evidence. The purpose of these speculations is just to suggest where to look for possible effects, if there are any.

6. Summary

We have presented a complementary approach to the treatment of electromagnetic interactions in a system. This treatment gives, in our opinion, a better feeling for what goes on inside a biological system. Energy is stored in the bulk and at interfaces. The energy is in the form of the energy of the electromagnetic fields of the normal-modes. These energies give rise to forces, dispersion forces, which in a biological system is at least as important as Coulomb forces. We ended by presenting some speculations as to where to look for possible effects from external electromagnetic fields.

Acknowledgements

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