TABLE 6
Selected Experiments on Biological Systems in Hypomagnetic (< GMF) Environments

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Staphylococcus aureus	Growth rate	5×10^{-2}	72 h	Fifteen-fold reduction in colony count at all dilutions, colony size also reduced compared with the control	21
Staphylococcus aureus 209P	Physiology, morphology, and catalase activity	10^{-5}	40 d	After subculture 18, hemolytic properties decrease steadily, alteration of pigment, fibrinolytic and coagulant ability lost, resistance to penicillin enhanced, catalase activity unaffected	164, 165
Streptococcus mutans	Exopolysaccharide accumulation on glass	5×10^{-3}	24 h 34°C	The preferential accumulation of exopolysaccharide on glass surfaces facing the north or south poles was abolished by reduction of the geomagnetic field	4
Azotobacter	Morphology, growth rate	$< 10^{-4}$	3–4 months	Changes in shape, size 6–8 times larger than control; filamentous and streptococcoid forms appeared among the cells	38
Diptheria bacillus	Morphology, fermentation, and enzyme activity	$< 10^{-5}$	Several days with daily subcultures taken	Subculture 5: coarse gray film with matte black slimy gelatinous colonies formed; Subculture 25: fermentation of most carbohydrates except for maltose; no difference in urease and cystinase activities compared to control	199
Serratia marcescens, *Alcaligenes faecalis*	Catalase activity	10^{-5}		Catalase activity steadily decreased with each subculture	165
Paracolon bacillus, *Salmonella typhimurium*, *Bacillus subtilis*	Catalase activity	10^{-5}		Catalase activity decreased in 1st to 6th subcultures	165

TABLE 6 (continued)
Selected Experiments on Biological Systems in Hypomagnetic (< GMF) Environments

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Sarcina and *Klebsiella*	Catalase activity	10^{-5}		Catalase activity increased and varied up to 6th subculture	165
Escherichia coli var. *communior*, *Bacterium prodigiosum* (*Serratia marcescens*), *Staphylococcus aureus* 209, and *Bacillus anthracoides*	Morphology, and biochemical properties	2×10^{-4}	2 months 37°C	Changes in pigment, morphological, cultural, and biochemical properties	228
Escherichia coli	Conjugation	10^{-5}		Variations and significant differences in frequency of R transmission in subcultures 56–60 (3–4 times greater), 80 and the later subcultures (2–10 times greater) compared with controls	166
Escherichia coli	UV survival	$2–15 \times 10^{-3}$	1 to 40 subcultures 37°C	UV tolerance increases when GMF reduced 160-fold, and decreases when GMF reduced 40-fold; effect dependent on exposure, and was reversible when stimulated by an artificial field of the same strength as the GMF	7
Chlorella and *Euglena algae*	Growth	$< 10^{-3}$	1–3 weeks	Enhancement of growth rate	90
Paramecium	Growth	$< 10^{-3}$	1–3 weeks	Enhancement of growth rate	90
Fungi (*Aspergillus*)	Morphology	10^{-4}	2 years	No morphological changes	38
Fungi (*Penicillum*)	Morphology	10^{-4}	2 years	No morphological changes	38

and suggest that bacteria and other microorganisms can be adversely affected by a substantial attenuation of the GMF. This is not surprising since bacteria have been exposed to the natural magnetic field throughout evolutionary periods of time. Adverse effects vary from a reduction in growth rate to morphological changes. Perturbations at the genetic level, such as variations in R transmission frequency, have also been reported (Pavlovich, 1975). Nevertheless, an enhancement of microbial viability such as a stronger resistance to penicillin and UV radiation has also been reported (Pavlovich and Sluvko, 1975; Alferov and Kuznetsova, 1981). A reduction in the magnetic environment of some algae and protozoa enhanced their growth rates (Halpern, 1966), whereas fungi did not seem to be affected (Chuvaev, 1969). The previously mentioned preferential accumulation of *Streptococcus mutans* bacteria on the south sides of glass was not observed when the GMF was reduced by 90% (Adamkiewicz et al., 1987). No explanation was provided for these observations.

VI. THEORETICAL MODELS

The relationship between external magnetic fields and the resulting local and internal fields should be explored to understand how magnets could influence biological treatment processes. The interaction between an applied magnetic field and a biological system involves several events. Usually, changes in an microorganism resulting from a reaction to an external factor can be detected only at the phenotypic or macroscopic levels, while the molecular processes underlying these changes remain obscure. On the other hand, observations from studies at the molecular level may not necessarily be the primary cause of the changes occurring at higher levels of organization. Results from *in vitro* investigations on molecular processes should be taken with caution because the ability for components of a system to react in a particular way to certain stimuli may be a feature for only that system with that particular level of complexity. The components of this system may either react differently to a stimulus or not react to it at all.

There are several mechanisms by which a magnetic field could influence a biological treatment process, including effects on the regulation of biochemical processes related to the biodegradation rate. Some of these ideas are presented along with supporting evidence.

A. Liquid Crystal Properties

A biological treatment process could conceivably be altered through the interaction of a magnetic field with the cell membrane or with other intracellular constituents of a cell that exhibit liquid crystal properties (Labes, 1966; Fergason and Brown, 1968). A magnetic field might cause sufficient macromolecular reorientation within a cell to affect charge transport, diffusion, growth, and degradation

rates. For example, the melting curve and relaxation behavior of DNA is similar to liquid crystals. In addition, many enzymes posses allosteric forms which are present in stacked molecular aggregates, and the small amount of energy required for structural changes (e.g., phase transitions) can be ascribed to liquid crystal properties. Albeit, the phospholipid membranes are the cell organelles showing liquid crystal properties most clearly.

Most microorganisms exhibit a sharp temperature dependent behavior in their proliferation and survival (Silver and Cornelius, 1974). At the molecular level, several thermal transition points have been shown to occur in solutions of cell membrane components (Steim, 1968). Nevertheless, the biological significance of these data should be regarded carefully since the structure and thermal behavior of cell membranes is much more complex than that of pure organic substances.

B. Diamagnetic Properties of Membranes

The diamagnetic nature of the phospholipid molecules in the cell membrane could also cause the molecules to interact with a magnetic field. The net reorientation of membrane phospholipids could then affect membrane transport channels in such a way that changes in the kinetics of membrane processes, such as diffusion and transport of nutrients, could occur. Because these processes are related to cell synthesis and biodegradation, alterations of the cell membrane would ultimately affect biological treatment processes to some degree.

There is a large body of evidence for the magnetic orientation of biological and cellular materials. Bacteriophage fibers (Torbet and Maret, 1979), bacterial chromatophores (Clement-Metral, 1975), chloroplasts (Geacintov et al., 1972), membranes [Hong, 1977], [Neugebauer et al., 1977] and macromolecules (Maret and Dransfeld, 1977) including nucleic acids have aligned in magnetic fields. These molecular ensembles posses a diamagnetic anisotropy that is defined by vectors corresponding to molecular axes. These diamagnetic susceptibility vectors dictate the molecular orientation with respect to the direction of the magnetic field. In an external magnetic field, a non-spherical molecule will experience a torque which aligns the molecule in such a way that the least negative diamagnetic susceptibility vector is parallel to the field. For a cylindrical molecule with axial symmetry, the degree of orientation is related to the diamagnetic anisotropy (Maret and Dransfeld, 1977). A molecule having a positive diamagnetic anisotropy will be aligned by an external magnetic field such that the long axis is parallel to the direction of the field. Molecules possessing a negative diamagnetic anisotropy will be oriented perpendicular to the field direction. The degree of orientation may be small for single molecules regardless of their diamagnetic anisotropy because they are more susceptible to the randomizing from thermal energy that tends to overcome magnetic alignment. Nevertheless, for molecules aligned parallel to one another and linked by functional groups, the individual anisotropies will summate resulting in

an enhancement of the diamagnetic anisotropy (Maret and Dransfeld, 1977). Most of the diamagnetic anisotropy of lipids is due to the acyl chains, so biological membranes with a phospholipid bilayer structure (e.g., bacterial membranes) would be expected to have an enhanced magnetic anisotropy.

The magnetic energy gained by a group of molecules in the cell membrane is a function of the total molecular volume, applied field strength, and magnetic anisotropy. The smaller the magnetic anisotropy, the larger the size of the region containing oriented molecules that would be necessary to observe complete orientation. The magnetic interaction energy must surpass the thermal energy before magnetic reorientation starts to occur. For intact *Chlorella* cells, the magnetic energy for complete orientation (B = 10 kG) is 16 to 25 times larger than the thermal energy at room temperature (Geacintov, 1979). Therefore, the thermal noise would only have a small effect on the magnetic alignment of these algal cells in a 10,000 G field. Magnetic orientation of diamagnetically anisotropic domains in artificial phospholipid bilayers has also been reported [Gaffney and McConnell, 1974], and the kinetics of bilayer lipid membrane formation have been shown to be influenced by the orientation of the magnetic field (Simonov et al., 1986).

The cell membrane exists in either a highly ordered crystalline state (gel phase) at low temperatures or in a relatively disordered fluid state (liquid-crystal phase) at high temperatures. This reversible change in membrane structure occurs over a narrow temperature range and is due to a change in lipid acyl chains from a predominantly all trans-configuration to a more disordered state. In the gel phase, membrane lipids are tightly aligned as a result of van der Waals attraction forces between hydrocarbon chains, headgroup interactions, and the excluded volume effect of packed lipid molecules. With increasing thermal energy comes the transition of the low-energy trans-bonds in the lipid acyl chains to the disordered higher energy configuration. At the phase transition temperature, there is sufficient energy for abrupt disordering of these hydrocarbon chains that decreases the intermolecular interaction, increases the membrane surface area, and decreases its thickness.

A membrane in the liquid-crystal phase will have higher fluidity and therefore will be more readily deformed in a magnetic field. This concept was demonstrated by observing a magnetic orientation of phospholipid bilayers in the liquid-crystal phase, while no orientation occurred in the gel phase (Speyer et al., 1987). Such orientations of the macromolecules would undoubtedly have an effect on transmembrane permeability and substrate uptake kinetics. Aoki et al. (1990) reported that the adriamycin accumulation by leukemia cell suspensions exposed to a 4000-G magnetic field was lowered by 5 to 10% compared with no-field controls. Exposure to the same magnetic field only during efflux increased the adriamycin efflux from the cells by 5% compared with the no-field controls. Both studies were carried out at a temperature range corresponding to phase transitions in the membrane. No significant differences were found at lower temperatures, which suggests that magnetic exposure can have a marked effect on the cell membrane permeability at the phase transition temperature. Rosen and Rosen (1990) explained the erratic circu-

lar motion of *Paramecium bursaria* in a static magnetic field on a similar basis. A partial molecular realignment of the organism's cell membrane would alter ion-specific channels, leading to disruptions in ciliary functions and locomotion.

The gel-liquid crystal phase transition in a biomembrane occurs over a very small temperature range and is not a uniform process. Just before the transition temperature, the membrane consists of clusters of lipid molecules in the gel phase within a fluid liquid-crystal bilayer. These clusters exhibit a significant increase in the diamagnetic anisotropy (dubbed "super-diamagnetic") which depend on the size of the clusters. Magnetic orientation will start to occur in B field strengths > 2000 G up to a limiting value of about 20,000 G corresponding to complete magnetic ordering (Braganza et al., 1984). The cluster size decreases with increasing thermal energy until the bilayer is in the liquid crystal state. The boundary between the gel and liquid-crystal phases is especially vulnerable to physical stress and distortion by magnetically induced changes in cluster orientation. Existing evidence suggests that these effects may be reversible [Rosen, 1994].

C. Free Radical Reactions

Free radicals play a major role in many biodegradative processes. Many enzyme systems produce free radicals as intermediates in the conversion of substrate to products (Grissom, 1995; Stubbe, 1988; 1989). For example, several polycyclic aromatic hydrocarbons can be converted to carcinogenic free radicals by enzymatic attack by cytochrome P-450 or prostaglandin synthase (Marnett et al., 1978), and reductive dechlorination of numerous chlorinated pollutants proceeds through free radical intermediates (Vogel et al., 1987). Magnetic fields on the order of 10 to 100 G can affect chemical reactions by influencing the electronic spin states of reaction intermediates (Atkins, 1976; Bube et al., 1978). The breaking of a chemical bond can produce two radicals which either have anti-parallel spins (singlet state) or spins that are parallel (triplet state), depending on the spin configuration of the parent molecule. The radicals can recombine (and in most cases usually do) but only if the radical pair is in the singlet state will the bond be formed.

Interchange between the triplet and singlet radical pair states can occur as a result of each unpaired electron experiencing different local magnetic fields from nearby magnetic nuclei such as protons, and are called hyperfine interactions. In an externally applied magnetic field, the triplet state of the radical pair can have three possible configurations which result in three different energy states (Figure 5). The spins may be parallel in the direction of the field (the T_{+1} state) or in the opposite direction (the T_{-1} state), or they may be anti-parallel, but in phase, in the field direction (the T_0 state). The separation of these energy states, called the Zeeman effect, will depend on the magnitude of the applied magnetic field. These states will be populated equally, and at low-strength fields (< 100 G) all of the triplet radical pairs can turn into singlets.

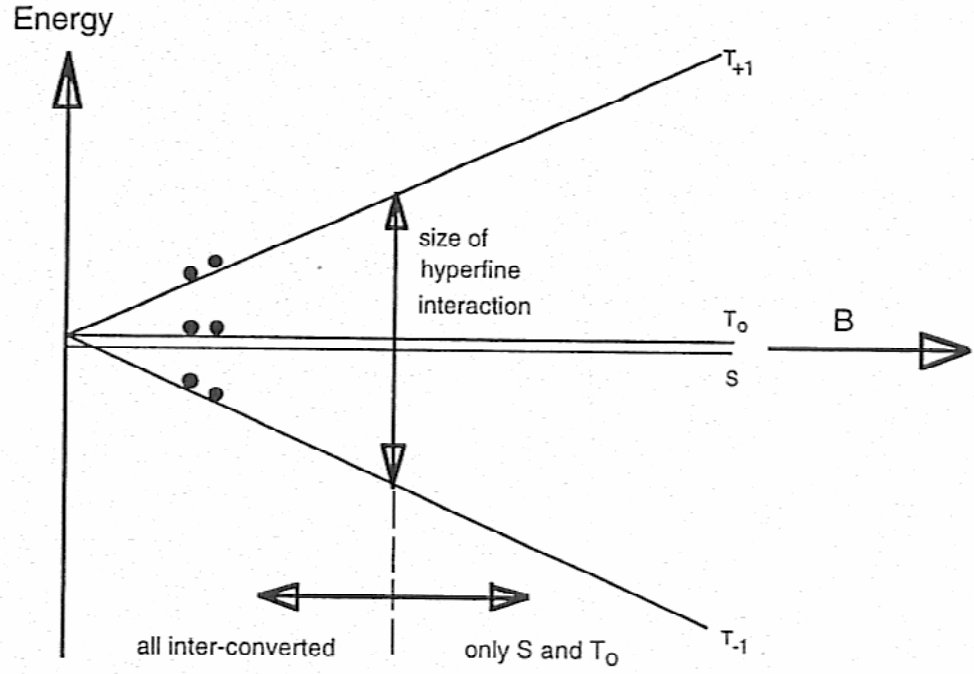

FIGURE 5. Zeeman diagram for a radical pair. The application of a magnetic field to an electron radical pair results in the separation of the energies that correspond to the triplet states, or $T_{\pm 1}$ levels. When the energy difference of the levels is less than the hyperfine interaction, then all the levels will be populated equally and radical pairs created in all the triplet states can be transformed into singlets (and vice versa) leading to recombination. As the field is increased beyond this value, the $T_{\pm 1}$ levels become decoupled from the others and radical pairs created in them cannot lead to recombination. (Adapted from McLaughlan, 1992.)

At some point, the applied field will be large enough that the Zeeman separation of the states exceeds the magnitude of the hyperfine interaction so that triplet-singlet interconversion cannot occur from the T_{+1} and T_{-1} states. This would reduce the probability of a radical-pair recombination as interconversion of up to two thirds of the triplet radical pairs have been stopped. Therefore, a magnetic field that is large enough to split the Zeeman energy levels of a radical pair can lead to changes in the rate of the reaction and product distribution. This could also have the end result of increasing the free radical concentration and lifetime, which could in turn increase the chances for the radical pair to separate and react with the cellular environment. This could be detrimental for microorganisms. If, on the other hand, free radicals are created as a result of the reaction of a singlet parent molecule, then at low fields the reactive singlet radical pair can turn into three unreactive triplet radical pairs following interconversion, whereas only one would

be possible in high fields. This is so because at high fields (> 100 G), the Zeeman separation of the triplet levels is larger than the magnitude of the hyperfine interaction, and only the T_o level can be populated by singlet-triplet intersystem level crossing. Therefore, the effect of a low magnetic field on the singlet radical pair can also reduce the probability of recombination. Singlet radical pairs created in a stronger magnetic environment (> 100 G) would not undergo intersystem crossing from the singlet to the triplet state because the hyperfine interaction between the nuclear and electron magnetic moment spins is insufficient to span the energy separation of the $T_{\pm 1}$ levels. Under this condition, the yield of triplet product would be theoretically reduced by two thirds in the external field. This has been experimentally confirmed using laser pulse excitation and optical absorption measurements with *Rhodopseudomonas sphaeroides* (Michel-Beyerle et al., 1979).

A similar variation has been proposed to account for the effects of magnetic fields on electron transport in photosynthetic, purple bacterial membranes (Schulten, 1982; Hoff, 1981; Blankenship et al., 1977). Since the photosynthetic apparatus is highly structured and membrane-bound, electron spin exchange interactions between ions formed during electron transport in the membrane could also affect the formation of the triplet state.

The effect of a magnetic field on Brownian rotation and diffusion of paramagnetic free-radical intermediates has been discussed by Valentinuzzi (1964, 1966). These processes might be important with respect to chemically effective collisions, such as production of free radicals or reactive sites on the enzyme or ribosome. For a reaction proceeding solely by rotational diffusion collisions, a field of 5000 G would reduce the reaction rate by only 1% (Valentinuzzi, 1964).

Magnetic field effects on radical-pair recombination have also been proposed to influence enzymatic reactions (Grissom, 1995). This theory, which is based on existing paradigms of chemistry and physics, considers the enzyme-substrate complex as a precursor to a radical pair. This radical pair could recombine into the enzyme-substrate complex or react further to form a product and a free enzyme. The rate of recombination of the radical pair affects the rate of catalysis, and it could be influenced by magnetic fields when the radical pair is weakly coupled and it exists long enough for interchange between triplet and singlet states to compete with other modes of reaction. These conditions are easier to meet when the enzyme has a relatively low affinity for the substrate and conformational changes that precede the formation of the radical pair are reversible (Grissom, 1995). Many enzyme-substrate systems may not satisfy these conditions and would not produce magnetic field-dependent reaction kinetics (Table 3).

D. The Josephson Junction Effect and Biological Superconductivity

The influence of very weak magnetic fields on the locomotion of the protozoan, *Paramecium caudatum* (Brown, 1962) and green algae, *Volvux aureus* (Palmer,

1963), illustrates the sensitivity of some organisms to small variations in the GMF (on the order of 10^{-4} G). This has led researchers to suggest that some organisms have a special mechanism for the detection of the GMF (Beischer, 1971; Cope, 1973; Marton, 1973). A physical mechanism based on superconductivity and the Josephson junction effect has been proposed to explain the sensitivity of biological objects to small changes in their magnetic environment (Cope, 1973).

Superconductivity is the total reduction of the electrical resistance of a conductor at low temperatures. In this state, the conduction electrons are in the lowest energy state and the majority, if not all, are paired with opposite spins and kinetic states (Cooper electron pairs). This will result in a complete loss of resistance and exclusion of any external magnetic field from the interior of the superconductor. The currents produced in such a system require no electromotive force and can flow without any loss of energy. The superconductivity current carried by paired electrons can flow not only in the semiconductor, but also between two semiconductors that are connected by a thin layer (100 to 200 nm) of ordinary conductor or dielectric with *no voltage drop*. This is the Josephson junction, named after the discoverer of the effect. Small changes in magnetic fields may produce large percent changes in Josephson current (Figure 6) even when a moderate value of constant magnetic field is present. The magnitude of the Josephson current has been theoretically predicted and experimentally observed to be markedly reduced by very weak magnetic fields due to electron interference effects. A decrease in the magnetic sensitivity is directly related to a decrease in the size of the Josephson junction or Cooper loop by the relation:

$$B_{min} = \frac{\Phi_0}{A} \qquad (1)$$

where B is the minimum magnetic field flux that can be sensed by an organism of cross-sectional area A, and Φ_o is a unit quantum of magnetic flux $\approx 2 \times 10^{-7}$ G-cm^2. For a cylindrical organism to sense a change in the magnetic field of 1 G, its required radius would have to be about 3 μm, which is in the size range of protozoa and some bacteria.

The possibility of this theoretical phenomenon occurring at physiological temperatures is indicated by effects shown for both organic molecules (e.g., cholates [Goldfein, 1974], and conjugated polymers [Little, 1964]) and biological (e.g., nerve tissues and *E. coli* growth rates (Cope, 1971), cell membranes [Cope, 1974; Marton, 1973], and DNA [Ladik et al., 1969]). The presence of cholesterol molecules in nerve-cell biomembranes may play a role in biological superconductivity for processes occurring in nerves (Cope, 1974). In addition, there is experimental evidence for superconduction in organic molecules of the bile acid type (Halpern and Wolf, 1972) and bimolecular layers composed of a metal and a semiconductor separated by organic molecules (Geballe, 1971). This structure is almost a perfect

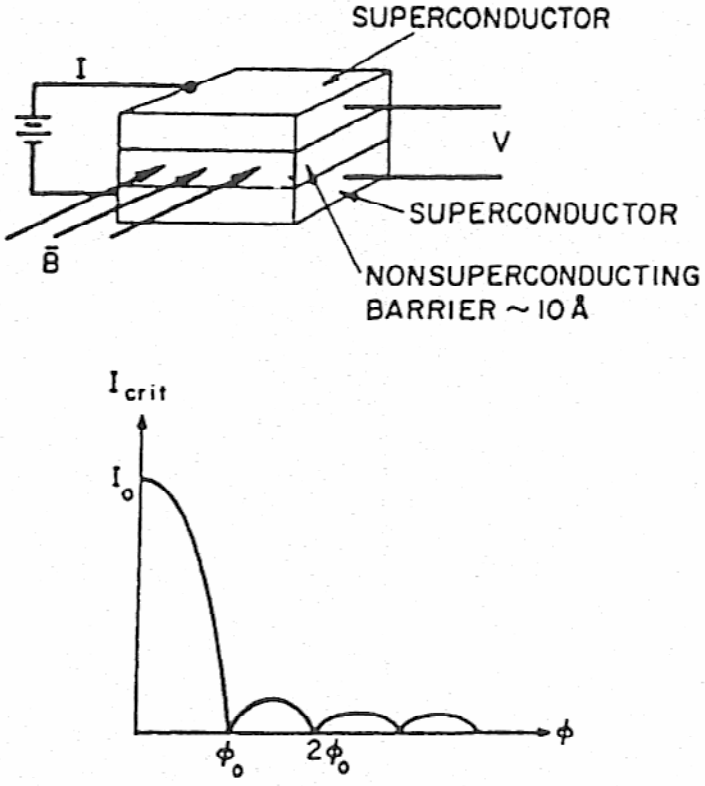

FIGURE 6. Change in zero potential I_o of Josephson current flowing through a bridge of area A, with an external field B directed along the junction. A small change in the magnetic field produces a large change in the Josephson current. Φ_o is a fixed unit of quantized magnetic flux $\approx 2 \times 10^{-7}$ G-cm^2. (Adapted from Cope, 1973.)

analog of phospholipid bilayers in microbial membranes (Figure 7). Other indirect evidence is the observed linear temperature dependence of conduction velocity in frog nerves and growth rate of *E. coli* (Cope, 1971) that show a negative temperature dependence analogous to that of electronic transitions occurring in Josephson junctions of a superconductor. Furthermore, electric fields as high as 100 kV/cm are present in nerve membranes and it has been shown that superconductivity can be observed in the presence of high electric fields at room temperature (Antonowicz, 1974).

It is conceivable then that fluctuations in a microorganism's magnetic environment caused by turning, movement in a low-gradient magnetic field, or even the natural fluctuations of the GMF might influence homeostatic and chemotactic

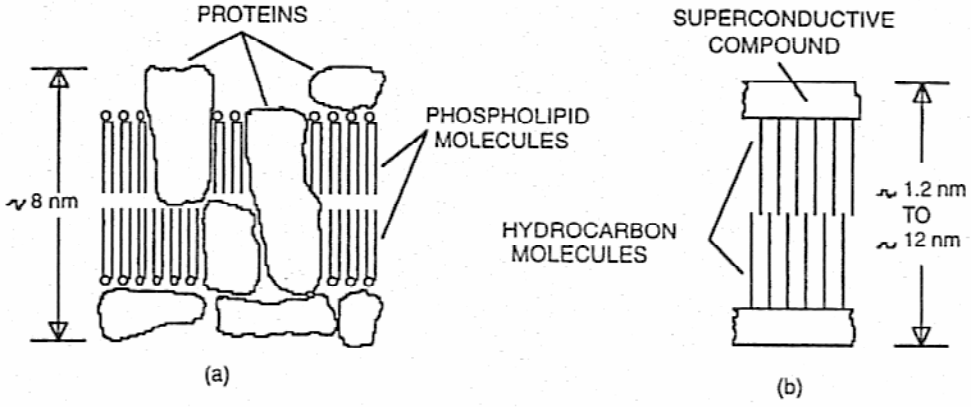

FIGURE 7. Schematic diagram of a typical cell membrane (a) and an intercalated superconductive film (b). The structure and dimensions are similar. (Adapted from Geballe, 1971 and Fox, 1972.)p

mechanisms and, to some degree, biodegradation rates. This may be important for some bacteria, and especially for larger microorganisms such as protozoa because magnetic sensitivity increases with size (Equation 1).

A major flaw regarding the hypothesis of biological superconductivity is that the effect of a magnetic field on Josephson currents is the same, irrespective of direction (polarity) (Figure 6), and therefore the use of the GMF by higher organisms for spatial orientation or homeostatic purposes is unclear. Dubrov [1978a] has pointed out, however, that the magnetic effects on the Josephson current is similar to the responses of fish and birds, which make equal use of both geomagnetic poles for orientation in space.

E. Bioenantiamorphism

The concept of bioenantiomorphism is an interesting viewpoint that was postulated to explain the occurrence in nature of different growth response of seedlings oriented towards the N and S poles of the GMF (Urmantsev, 1965, 1966, 1970, 1974; Urmantsev and Smirnov, 1962). The symmetry of natural objects is a fundamental property of living and non-living matter that can be either left-handed (L), right-handed (D), or intermediate (DL). Plants and seeds commonly show L and D forms (Figure 8) and can show different growth responses when the embryo is oriented toward the N or S magnetic pole [Sulima, 1970]. The symmetry of a root depends on the development of the lateral roots, whose disposition has been definitely correlated with the GMF (Pittman, 1963a, 1963b, 1964, 1965, 1967) and

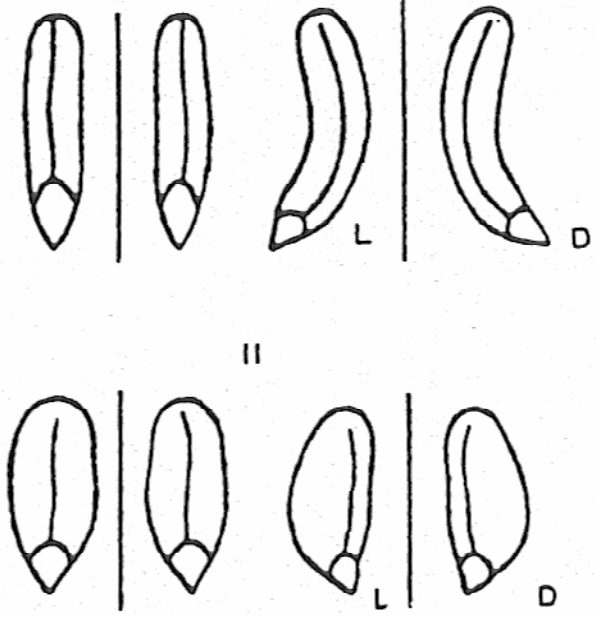

FIGURE 8. Diagram of left- (L) and right-handed (D) (based on position of endosperm) rye (I) and wheat (II) grains. (Adapted from Sulima, 1970).

hence the symmetry of the root is also influenced by the GMF. The dissymmetry of the florets of the red silk-cotton tree *Bombax ceiba* L. at different geographical points on the earth varied regularly according to how the dip of the GMF varied at that location (Davis, 1964). It has also been reported that alteration of the horizontal or vertical component of the GMF by Helmholtz coils led to a change in the orientation of the root creases of radishes (Noviskii and Markman, 1973). A response of bioenantioforms to the GMF has been shown to be genetically determined in sugar beets (Nikulin, 1975).

The north-south asymmetry in the GMF has been postulated as a possible cause of bioenantiomorphism (Dubrov, 1978c). The direction of the vertical component of the GMF is different in the southern hemisphere than the northern hemisphere. The ionospheric and magnetospheric currents that are a small variable component of the overall GMF are partially responsible for some asymmetry. Dubrov (1978c) hypothesized that the GMF may lead to the dissymmetry of water molecules and consequently to the functional and morphological asymmetry of biological objects that are largely composed of water. In particular, the structure of biological membranes is thought to include water molecules with atoms and electrons having different

orbital and spin magnetic moments that contribute to the overall dissymmetry of the membrane. In light of this argument, if the cell membrane has some dissymmetry associated with it, then this would cause a microorganism to be sensitive to orientation and direction with respect to the field lines of the GMF or a permanent magnet.

The GMF may also have a direct effect on the formation of enantiomeric biological molecules that are commonly found in bacterial cell membranes and constituents. A model for molecular evolution based on weak nuclear interactions and neutral currents at the quantum mechanical level was proposed as a possible cause for the chemical asymmetry of biological molecules (Garay and Hrasko, 1975). According to this model, the orbital electrons in chiral molecules have polarized spins associated with the direction of their motion. The direction of this motion may depend on the twist (left or right handed) of the helix of chiral molecules. The static charge in such a molecule is a helical potential field associated with electron motion, where an additional magnetic field formed around the electron interacts with the magnetic moment of the electron. Depending on the sign of the helix, the spin of the electron will be in the direction of its motion or in the reverse direction. The helical potential field, as a consequence of all this, will affect the coupling of spins and moments and alter the parity of the orbital electrons.

If the concept of orbital electrons with polarized spins is true, then the GMF could affect π-electron systems by altering the magnetic fields induced in chiral molecules, magnetic moments, spins, and, ultimately, current systems in them, which leads to a whole complex of potential biological abnormalities and behavior in artificial magnetic fields.

At the genetic level, the biosymmetric status of bacteria could be determined by the interaction of the GMF during the untwisting of a replicating chromosome, where the opportunity to interact with single stranded DNA is the greatest. At this moment, the enantiomorphic characteristic of the DNA template molecule would determine the direction of asymmetric synthesis and the stereoisomeric configuration of all the subsequent replicating molecules.

The GMF has also been proposed to influence the rythymicity of living organisms, in conjunction with the complex effect of many factors such as length of day, gravitation, atmospheric electricity, cosmic rays, light, temperature, and other external environmental factors. For example, the combined effect of the GMF and gravitation due to the lunar cycle of the moon was proposed to be responsible for the temporal and spatial organization of the planarian *Dugesia* (Brown and Park, 1965). Thus, the GMF could act as a synchronizer along with other external factors to control the cyclicity or rhythymicity of a biological treatment process.

Louis Pasteur observed that the amino acids of proteins in living organisms are of predominantly the L configuration, whereas when the same aminoacids are made chemically they consist of D and L forms (Duclaux, 1920). In this regard, it is not known whether exposure to a magnetic field could alter the in vivo production of polypeptides in such a way that diastereoisomers (having both L and D amino acid

components) are formed. Diastereoisomers of pentapeptides have been shown to increase the melanocyte-expanding activity by one to two orders of magnitude (Kastin et al., 1965). Conversely, there are many instances where polypeptide diastereoisomers containing D amino acids have produced a reduction in biological activity (Bentley, 1967). Table 7 lists several amino acids that have D-enantiomers that are known to be inhibitory to certain types of microorganisms. For example, L-alanine is common among proteins, but D-alanine has an inhibitory effect on *E. coli*, a common member of activated sludge consortia. Therefore, depending on the microbial species, a magnet-induced racemization of aminoacids could have both beneficial and detrimental effects.

Cellular uptake of enantiomeric amino acids and carbohydrates has also received attention. Eukaryotic cells preferentially transport L amino acids, but this is not an absolute requirement (Christensen, 1960; Johnstone and Scholefield, 1965). There appear to be different uptake sites with different stereochemical specificities for the transport of amino acids (Yoder et al., 1967).

F. Magnetic Forces Acting on Moving Microorganisms and Macromolecules

A magnetic field might influence biodegradation indirectly by affecting the motion of microorganisms or through destructive forces acting on the cell membrane. The magnetic forces and torques acting on macromolecular complexes can be calculated as a function of magnetic field strength using basic physical principles. Magnetotactic interactions between a uniform magnetic field and individual molecules (or cells) can be discounted unless the magnetic energy is at least of the same magnitude as the thermal energy. This is typically on the order of 10^6 to 10^7 G

TABLE 7
Some Bacteria Inhibited by D Amino Acids

Organism	Inhibitory amino acid as D-enantiomer	Ref.
Agrobacterium tumefaciens	Methionine, phenylalanine, tryptophan	27
Brucella abortus	Methionine, phenylalanine	234
Escherichia coli	Alanine; leucine; valine	114
Lactobacillus arabinosus	Leucine, valine, tryptophan (using low levels of L form)	64, 114, 175
Leuconstoc mesenteroides	Tryptophan (using low levels of L form)	175
Proteus X-2	Isoleuicine, valine	188
Rhizobium leguminosarum	Leucine	188

(Roberts, 1970). In a uniform field, strengths of 10^5 to 10^6 G would be required to produce torques sufficient for rotational alignment of asymmetrical objects. It is conceivable that a non-homogeneous field could disrupt a system at a weak point. To produce a stress of 1 dyne/cm (i.e., about the measured value of the tensile strength of cell membranes) would require a field of 300,000 G with a gradient on the order of 30,000 G/cm (Winterberg, 1967). However, experimental results have indicated cellular disruption at much lower fields and gradients (Levengood, 1969; Mulay and Mulay, 1964; Neurath, 1968, 1969). Intracellular particles with induced magnetic moments could also be accelerated by a strong magnetic field gradient. Winterberg (1966) estimated that for a 10-μm diameter particle, a 200,000 G magnetic heterogeneous field (–50,000 G/cm) could produce an accelerating g force of 1600 g on the cell wall.

One of the first attempts to explain the mechanism behind the interaction of magnetic fields with non-magnetotactic organisms was for the protozoan *Paramecium*. The motional electromotive force that would be generated by a *Paramecium* organism moving in a magnetic field could induce an electric field in its surroundings. Considering typical sizes (60×220 μm) and swimming velocities (0.1 cm/s), a magnetic field of 10^6 G would be necessary to induce an electric field sufficient to hinder its movement (Roberts, 1970). An evaluation of the induced dipole moment of the organism in a static magnetic field would require a minimum strength of 10^5 G to generate a sufficient torque to alter its movement. The action of a magnetic field on individual molecules was estimated, but neglected the interaction between magnetic domains in certain cellular structures. At normal temperatures, a magnetic field of 10^6 to 10^7 G was predicted to have enough magnetic energy to just surpass the thermal energy (Roberts, 1970).

Palmer (1963) observed that a weak magnetic field of 5 G increased the clockwise rotation of the alga *Volvox aureus* by 43 to 75%, depending on its orientation relative to the GMF. The locomotion of a *Paramecium* also became more circular after exposure to only 1.3 G (Brown, 1962). In a separate experiment, exposure of *Paramecium bursaria* to a 1260-G magnetic field decreased its free swimming velocity by 35% and resulted in more random and circular movement (Rosen and Rosen, 1990). These effects on motility are probably due to changes in the functions of membrane channels after partial realignment of anisotropic molecules in the cell membrane. This would either affect the Ca^{+2} transmembrane fluxes and regulatory processes, or lower the membrane resting potential. A lowered resting potential would change the ciliary beat angle and slow the beat frequency resulting in a consequent reduction in the swimming velocity (see Section V.H). In addition, the increased probability of action potentials along with the associated Ca^{+2} influx would cause reversal of ciliary beating, which would increase the randomness in motility.

Various mechanisms have also been discussed dealing with the Lorentz force from the interaction of a magnetic field on a moving charged particle. Gualtierotti (Gualtierotti and Capraro, 1964; Gualtierotti, 1964) attributed a decrease in polar-

ization across frog skin to magnetic effects on Na^+ transport across cell membranes. Ambrose et al. (1963) first mentioned the possible distortion of ionic currents associated with protoplasmic movements, active transport, and mitosis, by strong magnetic fields. However, a theoretical analysis by Kinouchi et al. (1988) estimated that a magnetic field of 2 to 6×10^{10} G would be required for the Lorentz force to cause a 10% decrease in the diffusion of simple ions. A similar decrease in the diffusion of complex ions such as plasma proteins would require a field of about 10^{11} G. A threshold value of 3.3×10^6 G with a gradient of 33,000 G/cm would be required for a non-homogeneous field to influence the diffusion of plasma proteins in a physiological saline solution.

In consideration of the above, detrimental effects of magnetic and electrodynamical forces associated with physical stress, ionic currents, and protoplasmic movement would only be important at very high magnetic fields, on the order of 10^5 to 10^7 G. Lorentz forces would be negligible for field strengths on the order of the GMF or those commonly attainable in laboratories.

G. Magnetic Interaction with Water as a Possible Role in Observed Biomagnetic Effects

A magnetic field could influence biodegradation kinetics by altering the physiological properties of the microbial growth medium. It has been claimed that water exposed to a magnetic field was less hard and produced less scale than ordinary water (Minenko et al., 1962). Increases in the absorption coefficient of distilled water has been reported to depend on the strength of the applied magnetic field (Bruns et al., 1966). The wavelength of maximum absorption, however, remained constant, an indication that there was no dissociation or association of molecules. While some experiments with distilled water have reported an increase in surface tension, viscosity, and dielectric constant with increasing field strength (Joshi and Kamat, 1966; Klassen, 1973; Umanskij, 1965), these findings have not been universally reproduced. For example, Gonet (1985) did not detect any measurable changes in the dielectric constant, pH, or surface tension of static or moving distilled water in magnetic fields that ranged from 1200 to 8000 G. No magnetic effects were seen on pH or surface tension for static and moving tap water. Kubát and Söderlund (1968) report similar results for the density, viscosity and electrical conductivity of water. The contradictory nature of the results, lack of error analysis, and lack of adequate control in experimental conditions (e.g., water flow rate, temperature) in the majority of the former studies would make their conclusions subject to question.

Prior treatment of a culture medium to magnetic fields of various strengths resulted in a twofold increase in hybridoma CB-IFNA2.4 growth (Pedraza et al., 1992). Gemishev (1977) studied the growth of *Helianthus annuus* L in magnetically pretreated water (1575 G, 5 to 20 min) and found that the mitotic activity in

root meristems was inhibited after 1 d and stimulated after 5 d of growth. Kogan and Tikhonova (1965) reported that *Paramecia* accumulated at one end of a capillary (the end closest to the south pole of a magnet) containing water that was pretreated in a magnetic field. An explanation for this behavior was not offered.

It has been suggested that ortho to para transitions may take place in water molecules subjected to a magnetic field (Neprimerov et al., 1967). Transitions of water molecules from the *ortho* state, where the spins of the protons of the two hydrogen atoms are parallel, to the para state, where the spins are anti-parallel, would lead to the expulsion of dissolved substances from such regions. Other mechanisms proposed include changes in ionic hydration, changes in the degree of hydrogen bonding, and Lorentz forces, to name a few.

If a magnetic field influenced the physiological properties of water, then it could also affect the intracellular water molecules to such an extent that cellular functions determining the biodegradation rate would also be affected.

H. Magnetic Field Effects on Ca^{+2} Regulation Processes

Ca^{+2} ions play such a crucial role in cellular functions such as stabilization of bacterial cell wall components and regulation of enzyme activity. Magnetic fields can affect processes that are regulated by the influx or outflux of Ca^{+2}. In particular, magnetic fields may alter the transport functions of the cell membrane, which governs the influx and outflux of Ca^{+2}. For example, the oriented growth of pollen tubes in intense magnetic fields (Sperber, 1981) might suggest that the redistribution of membrane proteins will alter the intracellular concentration of Ca^{+2}, and thus produce an inhibitory effect on a biological treatment process. There is an increasing amount of evidence that supports this view.

Ripamonti et al. (1982) postulated that magnetic fields prolong the lifetime of cytoplasmic Ca^{+2} transients indirectly through interactions with the cell membrane. The regulation of Ca^{+2} flux through the membrane was altered, creating a higher intracellular concentration. This was based on studies using the combined effects of a toxic drug and a magnetic field on the contraction cycle for the protozoan *Spirostomum ambiguum*. The magnetic field increased the extension phase cycle of contractions initiated by drug-induced increases in cytoplasmic Ca^{+2}, and had the overall effect of increasing the toxicity of the drug.

A magnetic field can also affect the ATP-energized Ca^{+2} transport in membranes of isolated muscle microsomes (Ettienne et al., 1979). The initial rate of Ca^{+2} uptake as well as total Ca^{+2} sequestered in the vesicles from avian pectoralis decreased linearly with increasing field strength above a threshold strength of about 500 G. Bucking et al. (1974) found that the contraction of isolated frog muscle, which involves regulation of intracellular Ca^{+2}, was affected by a magnetic field. A recent article by Itegin et al. (1995) reports the enhancement of Na^{+}-K^{+} ATPase and Ca^{+2} ATPase activities in diaphragm muscles isolated from rats that

were chronically exposed to a 200 G field. The Mg^{+2} ATPase activity, however, was not affected. Azanza (1989) found that magnetic fields mimic the inhibitory and excitatory actions of caffeine on neurons, another Ca^{+2}-dependent process.

Further evidence of magnetic field-induced changes in Ca^{+2} dependent processes was shown by the release of a lysosomal enzyme from a solution of human leukocytes after a 30 min exposure to a 10,000 G field (Papatheofanis et al., 1991). The effect was significantly inhibited by pretreatment with a calcium channel antagonist. Another study demonstrated that the frequency of acetylcholine release from nerve-diaphragms, which is related to the movement of Ca^{+2} through the presynaptic membrane, could be altered by exposure to a 1200 G static magnetic field (Rosen, 1992).

The ciliary functions of *Paramecia bursaria*, which is also highly dependent on Ca^{+2} regulatory processes, can be indirectly affected by magnetic field influenced disruptions or alterations of ion-specific membrane channels (Rosen and Rosen, 1990). Altered membrane properties and cell division rates in *Paramecium* that were caused by a pulsed magnetic field were abolished when a calcium blocking agent was introduced (Dihel, 1985).

Conversely, Bellossi (1986) observed no significant effects of a uniform or non-uniform magnetic field (2000 to 9000 G) on the amount of Ca^{+2} efflux from neonatal chick brains *in vitro*. A possible reason for the lack of observations may be that the experiment was carried out at 23°C, which is significantly different from the *in vivo* brain temperature of 38 to 39°C.

Recently, a controlled experiment demonstrated that the mechanism of magnetic interaction with biological systems may involve the hydration state the Ca^{+2} ion (Ayrapetyan et al., 1994a, 1994b). Various concentrations of $CaCl_2$ in water ranging from 10^{-5} to 10^{-1} *M* were exposed to a static magnetic field of 270 G for 2 min. For salt concentrations greater than 10^{-4} *M*, the conductivity of the solution decreased by up to 6%, and the effect persisted for at least 2 h after exposure. However, the same magnetic field had no effect on the conductivity of NaCl or KCl solutions regardless of concentration. These results suggest that the magnetic field affected the ability of Ca^{+2} to move, which is related to the size of the hydration sphere. Thus, magnetic fields could alter the hydration sphere of Ca^{+2} ions and their thermodynamic activity.

Further evidence supporting this hypothesis was obtained from studies involving snail neurons in physiologic saline solutions that were magnetically pretreated. Prior exposure of the solutions for 1 min to a 46 G and 380 G static magnetic fields reduced the amount of Ca^{+2} uptake by 62 and 74%. The study was extended to the measurement of the cyclic nucleotide levels that are involved in Na:Ca exchange processes regulating the quantity of intracellular Ca^{+2}. The content of cAMP and cGMP determined in the nerve tissue following a 10-min incubation in physiologic saline solutions that were previously exposed to a 250 G static magnetic field were significantly different than the no-field control. The lipid composition in a cell membrane is strongly dependent on intracellular Ca^{+2} ion concentration. When the

snail nerve tissue was incubated in a magnetically pretreated solution, the lipid composition was qualitatively and quantitatively different than that of the control ganglia.

In summary, experimental evidence suggests that magnetic fields may have an inhibitory effect on some Ca^{+2}-dependent processes, which could hinder biodegradation kinetics. The mode of action may be via the alteration of membrane transport channels and hence intracellular Ca^{+2} regulation, or by the alteration of the physical state of Ca^{+2} in solution, or both.

Incidentally, magnetic fields have a long and controversial history of application for the treatment of hard water (e.g., water containing high concentrations of Ca^{+2} ions). A recent literature review of antiscale magnetic treatment (AMT) cites various examples where magnetic fields reduced scale deposition, removed scale, or produced a softer and less tenacious scale (Baker and Judd, 1996). Apparently, scale inhibition and descaling could occur as a result of magnetically produced hydrophilic discrete scale particles of substantially different size and crystal morphology to untreated systems, in which more adherent crystal is generated. Nevertheless, AMT systems have also proven ineffective at some installations, and process industries remains skeptical of AMT technologies. Baker and Judd (1996) concluded that "... more widespread acceptance of AMT would result from a more comprehensive understanding of the mechanisms by which the process may operate".

I. Spin Interactions and Conformational Changes

A magnetic field could alter biodegradation kinetics by inducing conformational changes in enzymes that (Mulay and Mulay, 1964). Macromolecules containing transition metals, such as catalase, myoglobin, and cytochrome-c, should be especially sensitive to magnetic fields. The increase in activity of cytochrome-c oxidase from magnetic fields (700 to 7000 G) observed by Gorczynska et al. (1982) was attributed to interactions with the magnetic moments of paramagnetic ions in the enzyme. Changes in the orientation of the magnetic moments could result in changes in spin orientation of Fe^{+2} and Cu^{+2} ions (i.e., conversion between high-spin and low-spin states) that would cause changes in the electromagnetic field of the binding ligand. The resulting energetic changes could alter the enzyme conformation by breaking hydrogen bonds, causing dipolar interactions, and changing bond angles. Gross (1963; 1964) suggested that magnetic energies can distort and reorient bond angles of paramagnetic molecules. A 10^5 G field can be attained with most DC electromagnets and has sufficient magnetic energy to deform a tetrahedral bond angle in carbon by 1°. Such conformational changes could hinder the enzyme-substrate binding specificity sufficiently to produce an inhibitory effect on the rate of a biodegradative reaction. Nevertheless, conformational changes could also result in beneficial effects. For example, Young (1969) attributed an

increase in acetylchholinesterase hydrolysis to conformational changes caused by a magnetic field that enhanced the binding to the substrate.

J. Other Proposed Mechanisms of Interactions with Magnetic Fields

Neurath (1969) postulated that the protein complex of ferritin commonly found in cells would have sufficient paramagnetic susceptibility to be moved through the cell by to the gradient produced by a high strength non-uniform magnetic field. The movement of ferritin would set up a concentration gradient that would interfere with the formation of hemoglobin. This hypothesis, however, was not supported by the results of a non-uniform magnetic field (10,000 G, –8350 G/cm) on frog eggs. No ferritin aggregates were detected and a chemical analysis of various components of the embryos did not show a non-random distribution of iron.

Gill and Downing (1961) observed a 4% increase in the diamagnetic susceptibility of dead yeast and bacteria compared with live cells. They proposed that protoplasmic molecules existed in an excited (paramagnetic) state during life and reverted to a diamagnetic ground state after death.

The interaction of a magnetic field with paramagnetic dissolved oxygen (DO) molecules could be considered as a relevant mechanism, especially if a biodegradation reaction is aerobic. The accelerated removal of O_2 from the reaction site was proposed as a possible cause for the increase in catalase activity when exposed to a 60,000 G field (Haberditzl, 1967). Although there have been claims of a magnetic field affecting the redistribution of DO and partial pressure of O_2 (Lyu et al., 1978), a 3500 G field had no effect on the solubility or rate of dissolving O_2 in either water or in a 0.1 N NaCl solution (Ushakova et al., 1982). The distribution of DO under equilibrium conditions was not affected by a gradient magnetic field of 10,000 G (–1000 G/cm) (Ueno and Harada, 1982). However, the spatial distribution of non-equilibrium concentrations of DO in the same field gradient varied between 1 and 7%, depending on the temperature. The authors hypothesized that the spatial distribution of DO by magnetic fields is a secondary effect that is modulated by the magnetic redistribution of O_2 vapor over the solution. The effect of a heterogeneous magnetic environment on the diffusion of O_2 in water has also been considered (Kinouchi et al., 1988). The Maxwell stress required for a 10% decrease in diffusion was calculated to be 7.1×10^{11} G^2/cm. This value, however, is practically unattainable even with thin wires that can achieve very high field gradients.

A quantum mechanical model presented by Barnothy (1964, 1966) describes the interaction mechanism by which magnetic fields affect the strength of hydrogen bonds of the double-stranded DNA helix. The attractive force on the shared proton from the lone pair of electrons on the purine and pyrimidine bases can be represented by a double-well potential separated by a potential barrier. The wells represent the equilibrium position of the protons. The magnetic fields affects the rate of proton tunneling (i.e., the non-zero probability that a proton passes through

the potential barrier). Barnothy postulated that the magnetic field might (1) affect the spin orientation of the tunneling proton, (2) produce an accelerating force on a proton that enhances or retards its tunneling in a given direction (for heterogeneous fields), and (3) change the depth of the potential wells, thus changing the tunneling probability. Changes in the rate of proton tunneling might increase the probability for the formation of tautomeric base pairs. If replication by the breaking of hydrogen bonds occurs before the original state is restored, then the base tautomers would have to attach to different complementary bases. This would change the base sequence resulting in mutagenic effects. Nevertheless, a critical review of the genotoxic potential of magnetic fields concluded that static magnetic fields up to 10,000 G are not mutagenic to microbes (McCann et al., 1993). The majority of the evidence also suggests that static magnetic fields ranging from 450 to 10,000 G do not produce genetic abnormalities in *Drosophilia* (fruitflies) or in mammalian cells *in vitro*.

In summary, theoretical models suggest that there are many possible mechanisms by which static magnetic fields could affect biological treatment processes, with either beneficial or detrimental results. Mechanisms based on classic physical principles typically require very high field strengths produced by superconducting magnets to exert an appreciable stress on a biological system. Such mechanisms, therefore, cannot explain many observed biological responses at low and moderate field strengths. Which mechanism is partially or fully responsible for observed effects under certain experimental conditions remains to be clarified and will require further research. It is also plausible that a magnetic field may affect biodegradation simultaneously in more than one manner, or that even a synergistic relationship may exist between a particular interaction mechanism and one or several others.

VII. CONCLUSIONS AND PERSPECTIVE FOR FUTURE RESEARCH

A significant body of evidence clearly indicates that static magnetic fields can influence some biological and biochemical systems. Many of these effects can be explained by existing paradigms of chemistry and physics, such as free radical reactions and influx or outflux of ions through cell membranes. Potentially favorable changes in intracellular processes that could be exploited to enhance biological treatment have been observed in controlled studies. These include changes in enzymatic activities, growth and respiration rates, increased motility and membrane permeability, and morphological and developmental effects. While the underlying mechanism(s) responsible for these observations are not fully understood, the potential for beneficial as well as detrimental effects is consistent with calculations based on several fundamental laws of physics.

Studies that have focused on environmentally important biological processes and systems are recent but few in number. Further applied and basic research is needed to develop a better understanding and a more widespread acceptance of

magnetically modified biological treatment processes as an additional tool for pollution control. It is certainly plausible that a magnetic field may affect biodegradation simultaneously in more than one manner, or that even a synergistic relationship may exist between a particular interaction mechanism and one or several others. One has to remember that a living organism is a hierarchic organization with each stage of the complex system having its own specific properties that determine its interaction with other systems of the hierarchy and its reaction to external factors. It is difficult, if not impossible, to predict macroscopic effects on microbial cells and communities from studies of systems of a lower level of organization such as enzymes. While studies at all levels of biological organization are needed, studies with whole cells and mixed cultures should be the starting point to evaluate the feasibility of using magnetic fields in environmental engineering processes.

Ultimately, a design basis must be developed. Without unifying principles, however, such a basis is impossible. It is imperative to understand the relevant mechanisms over the entire range of field strengths to develop a rational basis for designing and optimizing appropriate treatment systems. Theoretical models should provide the dependence of effects on key parameters (e.g., field strength and gradient) and lead to quantitative predictions, including estimates of thresholds at which fundamental noise effects are exceeded by field effects and thresholds at which external field effects are no longer masked by biological background fields.

Microorganisms may display a higher sensitivity to the absence of the Earth's natural magnetic field than environments where it is artificially increased by several orders of magnitude. Under conditions of study involving low fields, great care must be taken to eliminate stray fields such as the ac magnetic fields produced by incubators and other electric motors, solenoids, and heating elements that might be nearby. Residual magnetization in ferromagnetic materials used in building construction can significantly perturb the local geomagnetic field. Residual magnetization in building materials after welding, forming, or machining could make measurable contributions to the dc magnetic field in a room. Permanent magnets that can influence the ambient dc magnetic field can be found in common laboratory objects such as magnetized tools, magnetic door latches, universal motors, and magnetic seals on refrigerators (Misakian et al., 1993).

Currently, it is impossible to get a complete picture of how magnetic fields might affect biodegradation because of our incomplete understanding of the physiological processes occurring within the microbe(s). Nevertheless, past studies provide valuable insight for the interpretation of future experiments with magnetic fields and biological treatment processes. For example, a biological response that exhibits a linear dependence on magnetic exposure time reflects the cumulative nature of biomagnetic effects (Barnothy, 1966). Conversely, abrupt changes in a specific biological function can often be ascribed to local or generalized structural or conformational changes. The effects of magnetic forces that can cause molecular reorientation should be seen most easily at temperatures corresponding to tran-

sitions between different physical and structural phases (Aceto et al., 1970). Away from a transition point, it may take a much greater field to cause structural rearrangements that lead to functional changes. Magnetic fields would especially affect intracellular enzymes when they are incorporated in a multimolecular structure that is near a transition point. Weak magnetic fields might elicit responses that are not observable in commonly used experimental time frames. Intense fields might influence multiple systems (e.g., biochemical or physiological) simultaneously or selectively. Any biological influence that magnetic fields do exert may be detectable only in cases of fairly prolonged exposure of complex sequences of cellular or biochemical events rather than in systems involving the instantaneous application of a direct magnetic force after a single, specific chemical reaction. Conclusions regarding the interaction of a magnetic field with bacteria should be based on a set of complementary experiments. Any conclusions based on fragmentary data should be subjected to careful scrutiny.

In summary, converging lines of evidence suggest that enhanced microbial degradation of environmental pollutants by static magnetic fields is a bona fide phenomenon. Previous work suggests that the rates (and perhaps the selectivity) of biotransformations could be favorably affected. The main research questions of engineering relevance relate to determining which processes are susceptible to enhancement by manipulation of the magnetic environment, how the use of magnetic fields would be implemented (especially at a large scale), and the cost-to-benefit ratio. Such research should lead to a more widespread acceptance of magnetically modified biological treatment processes as an additional tool for pollution control.

ACKNOWLEDGMENTS

This review was conducted under the sponsorship of the National Science Foundation's Career Award to Prof. Alvarez.

REFERENCES

1. Abler, R. A., Magnets in biological research, in, *Biological Effects of Magnetic Fields*, Barnothy, M. F., Ed., Plenum Press, New York, 1969, 2, 1–27.
2. Aceto, H., Jr., Tobias, C. A., and Silver, I. L., Some studies on the biological effects of magnetic fields, *IEEE Trans. Magn.*, 6, (2) 368-373, 1970.
3. Adamkiewicz, V. W. and Pilon, D. R., Magnetic stimulation of polysaccharide accumulation in cultures of *Streptococcus mutans*, *Can. J. Microbiol.*, 29, 464–467, 1983.
4. Adamkiewicz, V. W., Bassous, C., Morency, D., Lorrain, P., and LePage, J.-L., Magnetic response in cultures of *Streptococcus mutans* ATCC-27607, Exp. Biol. (*Berlin*), 46, (3) 127–132, 1987.

5. Ahmed, N. A. G., et al., Evidence for collective magnetic effects in an enzyme; likelihood of room temperature superconductive regions, *Phys. Lett.*, 53A, 129, 1975.
6. Akoyungolou, G., Effect of a magnetic field on carboxydismutase, *Nature*, 202, (4931) 452–454, 1964.
7. Alferov, O. A. and Kuznetsova, T. V., Effect of an attenuated geomagnetic field on Escherichia coli UV ray resistance, *Kosm. Biol. Aviakosm. Med.*, 15 (4), 57–58, 1981.
8. Ambrose, E. J., Shepley, K., and Bhisey, A. N., Effects of magnetic fields on cell growth *in vitro*, *Br. Empire Cancer Campaign*, Forty-First Annu. Rep. (Part II), 125, 1963.
9. Antonowicz, K., Possible superconductivity at room temperature, *Nature*, 247 (5440), 358–359, 1974.
10. Aoki, H., Yamazaki, H., Yoshino, T., and Akagi, T., Effects of static magnetic fields on membrane permeability of a cultured cell line, *Res. Comm. Chem. Path. Pharm.*, 69 (1), 103–106, 1990.
11. Arajs, S., Yeh Lin, L. C. L., and Farrington, T. E., Behaviour of the action potential of *Nitella clavata* cells in the presence of uniform magnetic fields, *Proc. Int. Conf. Magn. Magn. Mater.*, American Institute of Physics, New York, 1975, 759-760.
12. Aristarkhov, V. M., Piruzyan, L. A., and Tsybyshev, V. P., The effect of a constant magnetic field on protein solutions, *Izv. Akad. Nauk. SSSR Ser. Biol.*, 0 (1), 44–53, 1977.
13. Atkins, P. W., *Chem. Br.*, 12, 214, 1976.
14. Ayrapetyan, S., Avanesian, A., Avetisian, T., and Majinian, S., Physiological effects of magnetic fields may be mediated through actions on the state of calcium ions in solution, in *Biological Effects of Electric and Magnetic Fields*, Vol. 1, 1994, 181–192.
15. Ayrapetyan, S. N., Grigorian, K. V., Avanesian, A. S., and Stamboltsian, K. V., Magnetic fields alter electrical properties of solutions and their physiological effects, *Bioelectromagnetics*, 15, 133–142, 1994.
16. Azanza, M. J., Steady magnetic fields mimic the effect of caffeine on neurons, *Brain Res.*, 489, (1), 195–198, 1989.
17. Baker, J. S., and Judd, S. J., Magnetic amelioration of scale formation, *Water Research*, 2, 247–260, 1996.
18. Barnothy, M. F., A possible effect of the magnetic field upon the genetic code, in *Biological Effects of Magnetic Fields*, Vol. 1, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 80–89.
19. Barnothy, M. F., Theoretical considerations of an effect of magnetic fields on spontaneous mutations, *Int. Biomagn. Symp., 3rd*, Abstract of Papers, Univ. of Illinois, Chicago, 1966.
20. Barnothy, J. and Forro, M., Lethal effect of cosmic ray showers on the progeny of animals, *Experientia*, 4, 1, 1948.
21. Becker, R. O., Relationship of geomagnetic environments to human biology, *New York State J. Med.*, 63, 2215–2219, 1963.
22. Beischer, D. E., The null magnetic field as reference for the study of geomagnetical directional effects in animals and man, *Ann. N.Y. Acad. Sci.*, 188, 324–330, 1971.
23. Bellossi, A., Lack of an effect of static magnetic field on calcium efflux from isolated chick brains, *Bioelectromagnetics*, 7, 381–386, 1986.
24. Bentley, R., Effect of diastereoisomerism on the hormonal activities of synthetic peptides, in *Molecular Asymmetry in Biology*, Vol. 1, Pergamon Press, New York, 1967, 251–257.
25. Blankenship, R. E., Schaafsma, T. J., and Parson, W. W., Magnetic field effects on radical pair intermediates in bacterial photosynthesis, *Biochim. Biophys. Acta*, 461, 297–305, 1977.
26. Blatt, F. J. and Kuo, Y., Absence of biomagnetic effects in *Nitella*, *Biophys. J.*, 16 (5), 441–444, 1976.
27. Bopp, M. Z., The inhibition of *Agrobacterium tumefaciens* by D aminoacids, *Naturforsch.*, 20b, 899–905, 1965.

28. Braganza, L. F., Blott, B. H., Coe, T. J., and Melville, D., The superdiamagnetic effect of magnetic fields on 1 and 2 component multilamellar liposomes, *Biochim. Biophys. Acta*, 801 (1), 66–75, 1984.
29. Brown, F. A., Jr., Responses of the planarian, *Dugesia*, and the protozoan, *Paramecium*, to very weak horizontal magnetic fields, *Biol. Bull.*, 123, 264, 1962.
30. Brown, F. A., Jr. and Park, Y. H., Phase-shifting a lunar rhythm in planarians by altering the horizontal magnetic vector, *Biol. Bull.*, 129 (1), 79–86, 1965.
31. Bruns, S. A., et al., Change in light extinction by water after exposure to a magnetic field, *Kolloidn. Zh.*, 28, 153, 1966.
32. Bube, W., Haberkorn, R., and Michel-Beyerle, M. E., Magnetic field and isotope effects induced by hyperfine interactions in a steady-state photochemical experiment, *J. Am. Chem. Soc.*, 100, 5953, 1978.
33. Bucking, J., Herbst, M., and Pointer, P., The influence of a strong magnetic field on muscular contraction" *Radiat. Environ. Biophys.*, 11, 79–85, 1974.
34. Cheveneau, C. and Bohn, G., The interaction of a magnetic field on *Infusoria*, *Comptes. Rendu. Acad. Sci.*, 136 (25), 1579–1580, 1903.
35. Chizhevskii, A. L., One form of the specifically bioactive or Z-emission of the sun, in *The Earth in the Universe*, Mysl', Moscow, 1964, 342.
36. Chizhov, S. V., Sinyak, Yu, E., Shikina, M. E., Ukhanova, S. I., and Krasnoshchekov, V. V., Effect of a magnetic field on *Escherichia coli, Kosm. Biol. Aviakosm. Med.*, 9, (5), 26–31, 1975.
37. Christensen, H. N., Reactive sites and biological transport, in *Advances in Protein Chemistry*, Vol. 15, Anfinsen, C. B., Jr., Bailey, K., Anson, M. L., and Edsall, J. T., Eds., Academic Press, New York, 1960, 239.
38. Chuvaev, P. P., Effect of an extremely weak steady magnetic field on seedling root tissues and some microorganisms, in *Materials of 2nd All-Union Conf. on Effect of Magnetic Fields on Biological Objects*, Moscow, 1969, 252.
39. Clement-Metral, J. D., Direct observation of the rotation in a constant magnetic field of highly organized lamellar structures, *FEBS Lett.*, 50 (2), 257–260, 1975.
40. Conley, C. C., Effects of near-zero magnetic fields upon biological systems, in *Biological Effects of Magnetic Fields*, Vol. 2, Barnothy, M. F., Ed., Plenum Press, New York, 1969, 29–51.
41. Cook, E. S., Fardon, J. C., and Nutini, L. G., Effect of magnetic fields on cellular respiration, in *Biological Effects of Magnetic Fields*, Vol. 2, Barnothy, M. F., Ed., Plenum Press, New York, 1969, 67–78.
42. Cook, E. S. and Smith, M. J., Increase of trypsin activity, in *Biological Effects of Magnetic Fields*, Vol. 1, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 246–254.
43. Cope, F. W., Evidence from activation energies for superconductive tunneling at physiological temperatures, *Physiol. Chem. Phys.*, 3, 403–410, 1971.
44. Cope, F. W., Biological sensitivity to weak magnetic fields due to biological superconductive Josephson junctions?, *Physiol. Chem. Phys.*, 5, 173–176, 1973.
45. Cope, F. W., Enhancement by high electric fields of superconduction in organic and biological solids at room temperature and a role in nerve conduction, *Physiol. Chem. Phys.*, 6 (5), 405–410, 1974.
46. Cremer-Bartels, G., Krause, K., Mitoskas, G., and Brodersen, D., Magnetic field on the earth as additional Zeitgeber for endogenous rhythms?, *Naturwissenschaften*, 71 (11), 567–574, 1984.
47. Dardymov, I. V., The effect of water treated with a magnetic field on plant growth, *Proc. of Conf. on the Effect of Magnetic Fields on Biological Objects*, Moscow, 1966, 25.
48. Davis, T. A., Possible geophysical influence of asymmetry in coconut and other plants, in *Working Party on Coconut Production, Protection and Processing*, FAO Technical Report, Colombo, Ceylon, 1964.

49. Dihel, L. E., Smith-Sonnenborn, J., and Middaugh, L. R., Effects of an extremely low frequency electromagnetic field on the cell division rate and plasma membrane of *Paramecium tetraurelia*, *Bioelectromagnetics*, 6, 61–71, 1985.
50. Dubrov, A. P., Dissymmetry of biological reactions and the geomagnetic field, in *Reaction of Biological Systems to Weak Magnetic Fields*, Moscow, 1971, 9.
51. Dubrov, A. P., Some aspects of heliobiological responsibility for rhythmicity in elements of biosphere, in *Lectures in Memory of L. S. Berg*, Vol. XV–XIX, Nauka, Leningrad, 1973a, 233.
52. Dubrov, A. P., Functional symmetry and dissymmetry of biological objects, *Zh. Obshch. Biol.*, 34 (3), 440, 1973b.
53. Dubrov, A. P., Effect of geomagnetic field on genetic homeostasis, in *Investigation of Species Productivity in Range*, Mintis, Vilnius, 1975, 168.
54. Dubrov, A. P., Sensitivity of living organisms to the GMF and biological superconductivity, in *The Geomagnetic Field and Life*, Plenum Press, New York, 1978a, 149.
55. Dubrov, A. P., Effect of geomagnetic field on genetic homeostasis, in *The Geomagnetic Field and Life*, Plenum Press, New York, 1978b, 87–116.
56. Dubrov, A. P., Possible causes of biological symmetry and dissymmetry, in *The Geomagnetic Field and Life*, Plenum Press, New York, 1978c, 131138.
57. Duclaux, D., *Pasteur, The History of a Mind*, Saunders, Philadelphia, 1920, 29.
58. Erygin, G. D., Pchelkina, V. V., Kulikova, A. K., Rusinova, N. G., Bezborodov, A. M., and Gogolev, M. N., Influence of the nutritional medium treatment of microorganisms by magnetic field on the growth and development, *Prikl. Biokhim. Mikrobiol.*, 24 (2), 257–263, 1988.
59. Ettienne, E. M., Ripamonti, A., and Frankel, R. B., Effect of magnetic fields on the drug-induced contractility of the ciliate *Spirostomum*, in *Magnetic Field Effect on Biological Systems*, Tenforde, T. S., Ed., Plenum Press, New York, 1978, 54–56.
60. Ettienne, E. M., Hoenig, P. A., and Frankel, R. B., Effect of DC magnetic fields on Ca^{+2} transport in isolated muscle microsomes, *Proc. URSI National Radio Science Meeting, Bioelectromagnetics Symposium*, Seattle, Washington, 1979, 442.
61. Fardon, J. C., Poydock, M. E. S., and Basulto, G., Effect of magnetic fields on the respiration of malignant, embryonic, and adult tissue, *Nature*, 211 (5047), 433, 1966.
62. Feinendegen, L. E. and Muhlensiepen, H., *In vivo* enzyme control through a stationary strong magnetic field: The case of thymidine kinase in mouse bone marrow cells, *Int. J. Radiat. Biol. Relat. Stud. Phys. Chem. Med.*, 52 (3), 469–480, 1987.
63. Fergason, J. L., and Brown, G. H., Liquid crystals and living systems, *J. Am. Oil Chemist's Soc.*, 45 (3), 120–127, 1968.
64. Fox, S. W., Fling, M., and Bollenback, G. N., Inhibition of bacterial growth by D-leucine, *J. Biol. Chem.*, 465–468, 1944.
65. Gaffney, B. J. and McConnell, H. M., Effect of magnetic field on phospholipid membranes, *Chem. Phys. Lett.*, 24 (3), 310–313, 1974.
66. Galar, I. and Martinez-Sanchez, J. L., Effects of variable magnetic fields on *Saccharomyces cerevisiae*, *Rev. Latinoam. Microbiol.*, 27 (4), 283–291, 1985.
67. Garay, A. S. and Hrasko, P., Neutral currents in weak interactions and molecular asymmetry, *J. Mol. Evol.*, 6 (2), 77–89, 1975.
68. Geacintov, N. E., Van Nostrand, F., Pope, M., and Tinkel, J. B., Magnetic field effect on the chlorophyll fluorescence in *Chlorella*, *Biochim. Biophys. Acta*, 226, 486–491, 1971.
69. Geacintov, N. E., Van Nostrand, F., Becker, J. F., and Tinkel, J. B., Magnetic field induced orientation of photosynthetic systems, *Biochim. Biophys. Acta*, 267, 65–79, 1972.
70. Geacintov, N. E., Orientation of biological membranes and cells in magnetic fields, in *Magnetic Field Effects on Biological Systems*, Tenforde, T. S., Ed., Plenum Press, New York, 1979, 46–48.
71. Geballe, T. H., New Superconductors, *Sci. Am.*, 225 (5), 22, 1971.

72. Gemishev, T. M., Influence of water, treated in a permanently magnetic field, on the mitosis in the meristem of the root of *Helianthus annuus* L., *God. Sofii. Univ. Biol. Fak.*, 68 (2), 89–94, 1977.
73. Genkhov, D., Cvetkova, A., and Atmazdov, P., The effect of the constant magnetic field upon the growth and development of *Trichomonas vaginalis, Folia Med. (Plovdiv)*, 16, 95–99, 1974.
74. Gerencser, V., Barnothy, M. F., and Barnothy, J. M., Inhibition of bacterial growth by magnetic fields, *Nature*, 196 (4854), 539–541, 1962.
75. Gerencser, V., Barnothy, M. F., and Barnothy, J. M., Inhibition of bacterial growth in fields of high paramagnetic strength, in *Biological Effects of Magnetic Fields*, Vol. 1, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 229–239.
76. Ghole, V. S., Damle, P. S., and Thiemann, W. H. P., Effect of magnetic field on ascorbic acid oxidase activity: I, *Z. Naturforsch. Sect. C Biosci.*, 41 (3), 355–358, 1986.
77. Gill, S. J., Magnetic susceptibility of single biological cells, Univ. of Colorado, Boulder, (Contract Non. 1147-(08)), Annual Progress Report, 1 June 1959 to 1 December 1959, Nov. 27, 1959, 7 p. AD 229 625.
78. Goldfein, S., Some evidence for high-temperature superconductivity in cholates, *Physiol. Chem. Phys.*, 6, 261–268, 1974.
79. Gonet, B., Influence of constant magnetic fields on certain physiochemical properties on water, *Bioelectromagnetics*, 6 (2), 169–176, 1985.
80. Goodman, E. M., Greenebaum, B., and Marron, M. T., Magnetic fields alter translation in *Escherichia coli*, *Bioelectromagnetics*, 15, 77–83, 1994.
81. Gopalan, H. N. B., Cordycepin inhibits induction of puffs by ions in *Chironomous salivary* gland chromosomes, *Experientia*, 29 (6), 724–726, 1973.
82. Gorczynska, E., Galka, G., Krolikowska, R., and Wegrzynowicz, R., Effect of magnetic field on activity of cytochrome oxidase not moved or moved relative to magnetic field lines, *Physiol. Chem. Phys.*, 14, 201–207, 1982.
83. Grissom, C. B., Magnetic field effects in biology: a survey of possible mechanisms with emphasis on radical-pair recombination, Environ. Chem., 1, 1995.
84. Gross, L., The influence of magnetic fields on the production of antibodies, *Biomed. Sci. Instrum.*, 1, 137–142, 1963.
85. Gross, L., Distortion of the bond angle in a magnetic field and its possible magnetobiological implication, in *Biological Effects of Magnetic Fields*, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 74–79.
86. Gualtierotti, T. and Capraro, V., The action of a magnetic field on the sodium transport across the cell membrane, in *Life Science and Space Research II. 4th International Space Science Symposium, 1963*, Warsaw, Florkin, M., and Dollfus, A., Eds., John Wiley and Sons, 1964, 311.
87. Gualtierotti, T., Decrease of the sodium pump activity in frog skin in a steady magnetic field, *The Physiologist*, 7, 150, 1964.
88. Haberditzl, W., Enzyme activity in high magnetic fields, *Nature*, 213, 72–73, 1967.
89. Haberditzl, W. and Muller, K., An external magnetocatalytic effect, *Angew. Chemie*, 76, 891, 1964.
90. Halpern, M. H., Effects of reproducible magnetic fields on the growth of cells in culture, NASA CR-75121, NASA, Washington, D.C., 1966.
91. Halpern, M. H. and Van Dyke, J. H., Very low magnetic fields: biological effects and their implications for space exploration, *Aerosp. Med.*, 37, 281, 1966.
92. Halpern, E. H. and Wolf, A. A., Speculations of superconductivity in biological and organic systems, in *Advances in Cryogenic Engineering*, Vol. 17, Timmerhaus, K. D., Ed., Plenum Press, New York; 1972, 109.
93. Harkins, T. T. and Grissom, C. B., Magnetic field effects on B_{12} ethanolamine ammonia lyase: Evidence for a radical mechanism, *Science*, 263, 958–960, 1994.

94. Hartell, W. K., Miller, D. A., and Abromavage, M. M., Project Sanguine's environmental compatability assurance program, in *Proc. IEEE Int. Electromagnetic Compatability Symp.*, 1972, 125.
95. Hedrick, H. G., Inhibition of bacterial growth in homogeneous fields, in *Biological Effects of Magnetic Fields*, Vol. 1, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 240–245.
96. Hodak, K., Horakova, D., and Kazdova, M., Homogeneous magnetic field effects on the distribution of yield of virulent staphylophage 812, *Folia. Fac. Sci. Natl. Univ. Purkynanae Brun. Biol.*, 0 (85), 17–32, 1987.
97. Hoff, A. J., Magnetic field effects on photosynthetic reactions, *Q. Rev. Biophys.*, 14, 599, 1981.
98. Hong, F. T., Photoelectric and magneto-orientation effects in pigmented biological membranes, *J. Coll. Interface Sci.*, 58, 471–497, 1977.
99. Horakova, D., Kazdova, M., and Nemec, M., Changes in the production of virulent staphylophage 812 depending on the time of cultivation of host cells of *Staphylococcus aureus* SA 812 in a homogeneous magnetic field before infection, *Folia. Fac. Sci. Nat. Univ. Purkynianae Brun. Biol.*, 0 (85), 33–42, 1987.
100. Isquith, I. R. and Bobrow, A., The effect of high intensity magnetic field on the entrance of various molecules into *Paramecium caudatum*, *Acta Protozool.*, 12, 125–131, 1973.
101. Isquith, I. R. and Swenson, J., Magnetic orientation in Paramecium caudatum, *Acta Protozool.*, 26 (3), 219–224, 1987.
102. Itegin, M., Gunay, I, Logoglu, G., and Isbir, T., Effects of static magnetic field on specific adenosine-5′-triphosphatase activities and bioelectrical and biomechanical properties in the rat diaphragm muscle, *Bioelectromagnetics*, 16, 147–151, 1995.
103. Jennison, M. W., The growth of bacteria, yeast, and molds in a strong magnetic field, *J. Bact.*, 33, 15–16, 1937.
104. Johnstone, R. M. and Scholefield, P. G., Amino acid transport in tumor cells, *Advances in Cancer Research*, Vol. 9, Haddow, A. and Weinhouse, S., Eds., Academic press, New York, 1965, 143–226.
105. Joshi, K. M and Kamat, P. V., Effect of magnetic field on the physical properties of water, *J. Indian Chem. Soc.*, 43, 620–622, 1966.
106. Jung, J., Sanji, B., Godbole, S., and Sofer, S., Biodegradation of phenol: A comparative study with and without applying magnetic fields, *J. Chem. Tech. Biotechnol.*, 56, 73–76, 1993.
107. Karavaev, V. G. Misuno, A. I., Rubenchik, A. Y., and Shimanovich, L. E., Toward the problem concerning the effect of a constant magnetic field on proteolytic enzymes, in *Teplomasso-perenos teplofiz. svoistva veshchestv*, Shashkov, A. G., Ed., 1974, 184–187.
108. Karlsen, A. G. and Aristarkhov, V. M., The effect of constant magnetic field on the rate of morphogenesis in the hydroid Clava multicornis, *Zh. Obshch. Biol.*, 46 (5), 686–690, 1985.
109. Kartashev, A. G., Kalyuzhin, V. A., and Migalkin, I. V., Effect of a weak magnetic field on the glycolysis rate in *Saccharomyces cerevisiae*, *Kosm. Biol. Aviakosm. Med.*, 12 (2), 76–77, 1978.
110. Kastin, A. J., Schally, A. V., Yajima, H., and Kubo, K., Melanocyte-stimulating hormone activity of synthetic MSH and ACTH peptides *in vivo* and *in vitro*, *Nature*, 207 (5000), 978–979, 1965.
111. Kimball, G. C., The growth of yeast in a magnetic field, *J. Bacteriol.*, 50, 109–121, 1938.
112. Kinouchi, Y., Tanimoto, S., Ushita, T., Sato, K., Yamaguchi, H., and Miyamoto, H., Effects of static magnetic fields on diffusion in solutions, *Bioelectromagnetics*, 9, 159–166, 1988.
113. Klassen, W. J., *Water and Magnet*, Nauka, Moscow, 1973, 93–105.
114. Kobayashi, Y., Fling, M., and Fox, S. W., Antipodal specificity in the inhibition of growth of *Escherichia coli* by amino acids, *J. Biol. Chem.*, 174, 391–398, 1948.
115. Kogan, A. B. and Tikhonova, N. A., The effect of a constant magnetic field on the movement of *Paramecia, Biofizika*, 10, 292–296, 1965.

116. Kogan, A. B., The possible mechanism of action of a constant magnetic field on the living cell, *Proc. Conf. on the Effect of Magnetic Fields on Biological Objects*, Moscow, 1966, 37.
117. Komolova, G. S., Erygin, G. D., Vasil'eva, T. B., and Egorov, I. A., Influence of a constant high-intensity magnetic field on the enzymatic hydrolysis of nucleic acids, *Dokl. Akad. Nauk SSSR Ser. Biol.*, 204, 995–997, 1972.
118. Kubát, J., and Söderlund, G., On the influence of weak magnetic fields on some physico-chemical properties of water and salt solutions, *Physikalische Chem.*, 1968, Neue Folge, Bd. 62, S: 180–187.
119. Kugot, A. S. et al., The effect of a constant magnetic field on *E. coli* enzyme activity, in *Translations on Biological Effects of Magnetic Fields*, NTIS, 1974 JPRS–62865.
120. Labes, M. M., A possible explanation for the effect of magnetic fields on biological systems, *Nature*, 211 (5052), 968, 1966.
121. Ladik, L., Biczo, G., and Redly, J., Possibility of superconductive-type enhanced conductivity in DNA at room temperature, *Phys. Rev.*, 188, 710–715, 1969.
122. Levashev, V. S., Gorshkov, M. M., Belokrysenko, S. S., and Davydova, M. G., Level of spontaneous phage production in an *E. coli* K_{12} lysogenic system as a test of solar activity, in *Effect of Some Cosmic and Geophysical Factors on the Earth's Biosphere*, Nauka, Moscow, 1973, 189–194.
123. Levengood, W. C., A new teratogenic agent applied to amphibian embryos, *J. Embryol. and Exp. Morphol.*, 21 (1), 23–31, 1969.
124. Lezzi, M. and Gilbert, L. T., Differential effects of K^+ and Na^+ on specific band of isolated polytene chromosomes of *Chironomous tentans*, *J. Cell Sci.*, 6 (3), 615–627, 1970.
125. Little, W. A., Possibility of synthesizing an organic superconductor, *Phys. Rev.*, 134 (6A), 1416–1424, 1964.
126. Lustigman, B. K. and Irwin, R. I., The enhanced lethality of Paramecium in dyes under the influence of magnetic fields, *Acta Protozool.*, 13 (21–27), 257–266, 1975.
127. Lyu, B. N., Efimov, M. L., Kul'Sartov, V. K., and Yakupova, R. M., Movement of liquid-dissolved oxygen in a constant magnetic field, *Biofizika*,23 (1), 159–161, 1978.
128. McCann, J., Dietrich, F., Rafferty, C., and Martin, A. O., A critical review of the genotoxic potential of electric and magnetic fields, *Mutation Res.*, 297, 61–95, 1993.
129. Magrou, J. and Manigault, P. C., Action of a magnetic field on the development experimental tumors in Pelagornium zonale, *Compt. Rend. Acad. Sci.*, 223 (1), 8–11, 1946.
130. Maling, J. E., Weissbluth, M., and Jacobs, E. E., Enzyme substrate reactions in high magnetic fields, *Biophys. J.*, 5, 767–776, 1965.
131. Malko, J. A., Constantinidis, I., Dillehay, D., and Fajman, W. A., Search for influence of 1.5 tesla magnetic field on growth of yeast cells, *Bioelectromagnetics*, 15, 495–501, 1994.
132. Maret, G. and Dransfeld, K., Macromolecules and membranes in high magnetic fields, *Physica B (Amsterdam)*, 86B–88B, 1077–1083, 1977.
133. Marlborough, D. I., Hall, D. O., and Cammack, R., Magneto-optical rotary dispersion (MORD) studies on spinach ferredoxin, *Biochem. Biophys. Res. Commun.*, 35, 410–413, 1969.
134. Marnett, L. J., Reed, G. A., and Denison, D. J., Prostaglandin synthase-dependent activation to 7,8-dihydroxybenzo[a]pyrene to mutagenic derivatives, *Biochem. Biophys. Res. Commun.*, 82, 210–216, 1978.
135. Marton, J. P., Conjectures on superconductivity and cancer, *Physiol. Chem. Phys.*, 5 (3), 259–270, 1973.
136. Misakian, M., Sheppard, A. R., Krause, D., Frazier, M. E., and Miller, D. L., Biological, physical, and electrical parameters for *in vitro* studies with ELF magnetic and electric fields, *Bioelectromagnetics Suppl.*, 2, 1–73, 1993.
137. Mazur, P. Ya, Effect of molecular oxygen saturation of *Saccharomyces cerevisiae* suspension in a magnetic field on yeast activity, *Prikl. Biokhim. Mikrobiol.*, 16 (4), 517–522, 1980.

138. McLaughlin, K., Are environmental magnetic fields dangerous?, *Physics World*, January, 41–45, 1992.
139. Mekshenkov, M. I., An investigation of the structure and conformation of ribonucleic acids by the method of birefringence in a magnetic field, *Biofizika*, 10, 747, 1965.
140. Michel-Beyerle, M. E., Scheer, H., Seidlitz, H., Tempus, D., and Haberkorn, R., Time-resolved magnetic field effect on triplet formation in photosynthetic reaction centers of *Rhodopseudomonas sphaeroides* R-26, *FEBS Lett.*, 100, 9, 1979.
141. Miller, D. A., Electric and magnetic fields produced by commercial power systems, in *Biological and Clinical Effects of Low Frequency Magnetic and Electric Fields*, Llaurado, J. G., Sances, A., Jr., and Battocletti, J. H., Eds., Charles C. Thomas, Springfield, IL, 1974, 67.
142. Minenko, V. I. et al., *Magnetic Treatment of Water*, 1962, Khar'kovskoe Knizhnoe Izd.
143. Miskiewicz, T. and Ziobrowski, J., The effect of magnetic field on activity of β-fructofuranosidase and on aerobic cultivation of baker's yeast, *Acta Aliment. Pol.*, 3 (4), 389–398, 1977.
144. Montgomery, D. J. and Smith, A. E., A search for biological effects of magnetic fields, *Biomed. Sci. Instrum.*, 1, 123–125, 1963.
145. Moore, R. L., Biological effects of magnetic fields: studies with microorganisms, *Can. J. Microbiol.*, 25 (10), 1145–1151, 1979.
146. Mulay, I. L. and Mulay, L. N., Effect on Drosophila melanogaster and S-37 tumor cells: postulates for magnetic field interactions, in *Biological Effects of Magnetic Fields*, Vol. 1, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 146–169.
147. Muller, K., Haberditzl, W., and Pritze, B., Examination of the influence of magnetic fields on chemical reactions, *Z. Phys. Chem. (Leipzig)*, 248, 185–192, 1971.
148. Nazarova, N. M., Livshitz, V. A., Anzin, V. B., Veselago, V. G., and Kuznetsov, A. N., Hydrolysis of globular proteins with trypsin in a strong magnetic field, *Biofizika*, 27 (4), 720–721, 1982.
149. Nemec, M., Horakova, D., and Kazdova, M., "Changes in dehydrogenase activity of cells of *Staphylococcus aureus* SA 812 after infection by phage 812 influenced by a homogeneous magnetic field, *Folia. Fac. Sci. Nat. Univ. Purkynianae Brun. Biol.*, 0 (85), 43–48, 1987.
150. Neprimerov, N. N., et al., The mechanism of the biological action of magnetic fields, in *Proceedings of Conference on the Effect of Magnetic Fields on Biological Objects*, Moscow, 1966, 48.
151. Neugebauer, D. C., Blaurock, A. E., and Worcester, D. L., Magnetic orientation of purple membranes demonstrated by optical measurements and neutron scattering, *FEBS Lett.*, 78 (1), 31–35, 1977.
152. Neurath, P. W., High gradient magnetic fields inhibits embryonic development of frogs, *Nature*, 219, 1358–1359, 1968.
153. Neurath, P. W., The effect of high-gradient, high-strength magnetic fields on the early embryonic development of frogs, in *Biological Effects of Magnetic Fields*, Vol. 2, Barnothy, M. F., Ed., Plenum Press, New York, 1969, 177–187.
154. Nikulin, A. V., Nature of orientation of root creases in left- and right-handed isomers of sugar beet in the geomagnetic field, in *Proc. 3rd All-Union Symp. Effect of Magnetic Fields on Biological Objects*, Kaliningrad State University, Kaliningrad, 1975, 18.
155. Nossol, B., Buse, G., and Silny, J., Influence of weak static and 50 Hz magnetic fields on the redox activity of cytochrome c oxidase, *Bioelectromagnetics*, 14 (4), 361–372, 1993.
156. Noviskii, Y. I. and Markman, E. V., Additional data on radish plants with different orientation of the root creases, in *Effect of Natural and Weak Artificial Magnetic Fields on Biological Objects*, Belgorod, 1973, 92–93.
157. Oak Ridge Associated Universities, Health effects of low-frequency electric and magnetic fields, *Environ. Sci. Technol.*, 27 (1), 42–51, 1993.

158. Oh, K. C. and Strom, P. F., Biodegradation of phenol with and without magnetic fields, Q-378 *Abst. 95th Annu. Meet. Am. Soc. Microbiol.*, Washington, DC, May 21–25, 1995.
159. Okuno, K., Ano, T., and Shoda, M., Effect of super high magnetic field on growth of *Escherichia coli*, *Biotech. Lett.*, 13 (10), 745–750, 1991.
160. Okuno, K., Tuchiya, K., Ano, T., and Shoda, M., Effects of super high magnetic field on the growth of *Escherichia coli* under various medium compositions and temperatures, *J. Ferment. Bioeng.*, 75 (2), 103–106, 1993.
161. Palmer, J. D., Organismic spatial orientation in very weak magnetic fields, *Nature*, 198 (4885), 1061–1062.
162. Pantev, T. P. and Minkova, M. I., Direct and indirect effects of constant magnetic field on biological objects, *Kosm. Biol. Aviakosm. Med.*, 20 (6), 73–76, 1986.
163. Papatheofanis, F. J., Barmada, R., Reyes, H., Greager, J. A., and Papatheofanis, B. J., Nifedipine inhibits magnetic field-induced lysosomal degranulation, *J. Bioelectr.*, 9 (2), 205–208, 1991.
164. Pavlovich, S. A., Conjugational R transmission in *Escherichia* in experiments with a fluctuating magnetic field, in *Proc. 3rd All-Union Symp. Effect of Magnetic Fields on Biological Objects*, Kalingrad State University, Kalingrad, 1975, 59–60.
165. Pavlovich, S. A. and Gumenyuk, V. A., Catalase activity of microorganisms cultivated for a long period in amagnetic conditions, in *Proc. 3rd All-Union Symp. Effect of Magnetic Fields on Biological Objects*, Kalingrad State University, Kalingrad, 1975, 58.
166. Pavlovich, S. A. and Sluvko, A. L., Effect of shielding from magnetic field on *Staphylococcus aureus*, in *Proc. 3rd All-Union Symp. Effect of Magnetic Fields on Biological Objects*, Kalingrad State University, Kalingrad, 1975, 56.
167. Pedraza, A., Duenas, M., Perez, M., Limonta, J., Suarez, N., Diaz, S., Lopez, G., Calderon, F., and Gavilondo, J., Magnetic treatment of culture medium for hybridoma growth, *Biotechnol. Tech.*, 6 (4), 329–334, 1992.
168. Petracchi, G., Checcucci, A., Gambini, O., and Falcone, G. G. Studies on bacterial growth: II. Effects of physical perturbations on bacterial growth, *G. Microbiol.*, 15, 189–196, 1967.
169. Pittman, U. J., Effects of magnetism on seedling growth of cereal plants, *Biomed. Sci. Instrum.*, 1, 117–119, 1963a.
170. Pittman, U. J., Magnetism and plant growth I. Effect on germination and early growth of cereal seeds, *Can. J. Plant Sci.*, 43, 513–518, 1963b.
171. Pittman, U. J., Magnetism and plant growth II. Effect on root growth of cereals, *Can. J. Plant Sci.*, 44, 283–287, 1964.
172. Pittman, U. J., Magnetism and plant growth III. Effect on germination and early growth of corn and beans, *Can. J. Plant Sci.*, 45, 549–555, 1965.
173. Pittman, U. J., Biomagnetic responses in Kharkov 22 M.C. winter wheat, *Can. J. Plant Sci.*, 47, 389–393, 1967.
174. Pollard, E. C., Pilot theoretical study of the effect of weightlessness and densely ionizing radiation on single cells, NASA, 1962.
175. Prescott, J. M., Schweiert, B. S., Lyman, C. M., and Kuiken, K. A., The effect of D-tryptophan on the utilization of the L isomer by some lactic acid bacteria, *J. Biol. Chem.*, 178, 727–732, 1949.
176. Presman, A. S., *Electromagnetic Fields and Life*, Plenum Press, New York, 1970, 199.
177. Putnam, F. W., Effect of temperature on the rate of protein denaturation, in *The Proteins: Chemistry, Biological Activity, and Methods*, Part B, Neurath, H. and Bailey, K., Eds., Academic Press, New York, 1953, 1, 864–866.
178. Rabinovitch, B., Maling, J. E., and Weissbluth, M., Enzyme-substrate reactions in very high magnetic fields. I, *Biophys. J.*, 7, 187–204, 1967a.
179. Rabinovitch, B., Maling, J. E., and Weissbluth, M., Enzyme-substrate reactions in very high magnetic fields. II, *Biophys. J.*, 7, 319–327, 1967b.

180. Rawls W. C., and Provell, G. J., Magnetically modified microbial metabolism, U.S. Patent Number 5,318,045, June 7, 1994.
181. Reno, V. R. and Nutini, L. G., Effect of magnetic fields on tissue respiration, *Nature*, 198 (4876), 204–205, 1963.
182. Ripamonti, A., Ettienne, E. M., and Frankel, R. B., Effect of homogeneous magnetic fields on responses to toxic stimulation in *Spirostomum ambiguum*, *Bioelectromagnetics*, 2 (2), 187–198, 1982.
183. Roberts, A. M., Motion of *Paramecium* in static electric and magnetic fields, *J. Theor. Biol.*, 27, 97–106, 1970.
184. Rosen, A. D., Magnetic field influence on acetylcholine release at the neuromuscular junction, *Am. J. Physiol. (Cell Physiol. 31)*, 262, C1418–C1422, 1992.
185. Rosen, A.D., Direct current magneyic fields: mechanisms of action, in *Biological Effects of Electric and Magnetic Fields*, Carpenter, D. O., and Ayrapetyan, S., Eds., Academic Press, New York, 1994, 165–192.
186. Rosen, M. S. and Rosen, A. D., Magnetic field influence on *Paramecium* motility, *Life Sci.*, 46, (21), 1509–1516, 1990.
187. Rostkowska, J. and Moskwa, W., The influence of magnetic field on susceptibility for toxic compounds in *Spirostomum ambiguum* Ehrb., *Acta Protozool.*, 5, 305–313, 1968.
188. Rydon, H. N., *Biochem. Soc. Symp. (Cambridge, Engl.)*, 1, 40, 1948.
189. Sachava, T. S. and Samokhvalova, L. I., Changes of the membrane potential of cells of alga *Nitella flexilis* under the infuence of direct magnetic field, *Biofizika*, 15 (5), 89–92, 1970.
190. Sato, K., Yamaguchi, H., Miyamoto, H., and Kinouchi, Y., Growth of human cultured cells exposed to a non-homogeneous static magnetic field generated by Sm-Co magnets, *Biochim. Biophys. Acta*, 1136, 231–238, 1992.
191. Schaarschmidt, B., Lamprecht, I., and Muller, K., Influence of a magnetic field on the UV sensitivity in yeast, *Z. Naturforsch.*, 29C, 447–448, 1974.
192. Schulten, K., Magnetic field effects in chemistry and biology, *Adv. Solid State Phys.*, 22, 61, 1982.
193. Shimuzu, H. Akiyama, M., Suzuki, Y., and Hayashy, K., The effects of magnetic field on mutagenic activity, *Mutat. Res.*, 216, 377, 1989.
194. Shires, T. K., Pitot, H. C., and Kaufman, S. A., The membrane: A functional hypothesis for the translation and regulation of genetic expression, in *Biomembranes*, Vol. 5, Plenum Press, New York, 1974, 81–145.
195. Shishlo, M. A., Influence of magnetic fields on enzymes, tissue respiration, and some aspects of metabolism in an intact organism, in *Influence of Magnetic Fields on Biological Objects*, Kholodov, Yu. A., Ed., NTIS, Springfield, Virginia, 1974, JPRS–36038.
196. Silver, I. L., and Tobias, C. A., Action of magnetic fields on liquid crystals, in *Space Radiation Biology and Related Topics*, Tobias, C. A. and Todd, P. W., Eds., Academic Press, New York, 1974, 274.
197. Simonov, A. N., Livshits, V. A., and Kuznetsov, A. N., Effect of a constant magnetic field on the formation of bilayer lipid membranes, *Biofizika*, 31 (5), 777–780, 1986.
198. Skopek, T., Fairfax, S., and Thilly, W. G., Cited by R. B. Frankel in Biological effects of static magnetic fields, in *CRC Handbook of Biological Effects of Electromagnetic Fields*, Polk, C., and Postow, E., Eds., CRC Press, Boca Raton, 1986.
199. Sluvko, A. L., Variation of diphtheria corynebacteria cultivated for a long period in a permalloy chamber, in *Proc. 3rd All-Union Symp. Effect of Magnetic Fields on Biological Objects*, Kalingrad State University, Kalingrad, 1975, 61.
200. Smith, M. J., Personal communication with Rabinovitch, B., Maling, J. E., and Weissbluth, M., Enzyme-substrate reactions in very high magnetic fields. II, *Biophys. J.*, 7, 319, 1967a.
201. Sperber, D., Dransfeld, K., Maret, G., and Weisenseel, M. H., Oriented growth of pollen tubes in strong magnetic fields, *Naturwissenschaften*, 68, 40, 1981.

202. Speyer, J. B., Sripada, P. K., Das Gupta, S. K., and Shipley, G. G., Magnetic orientation of sphingomyelin-lecithin bilayers, *Biophys. J.*, 51, 687–691, 1987.
203. Steim, J. M., Spectroscopic and calorimetric studies of biological membrane structure, *Advan. Chem. Ser.*, 84, 259–302, 1968.
204. Stubbe, J., Radicals in biological catalysis, *Biochemistry*, 27, (11), 3893–3900, 1988.
205. Stubbe, J., Protein radical involvement in biological catalysis?, in *Annu. Rev. Biochem.*, Vol. 58, Richardson, C. W., Abelson, J. N. Boyer, P. D., and Meister, A., Eds., Annual Reviews Inc., Palo Alto, Calif., 1989, 257–285.
206. Tenforde, T. S., Biological effects of stationary magnetic fields, in *Biological Effects and Dosimetry of Static and ELF Electromagnetic Fields*, Grandolfo, M., Michaelson, S. M., and Rindi, A., Eds., Plenum Press, New York, 198?, 93–127.
207. Thiemann, W. and Wagner, E., The influence of homogeneous magnetic fields on the growth of Micrococcus denitrificans, *Z. Naturforsch.*, 25b (2), 1020–1023, 1970.
208. Thomas, A. and Morris, P. G., The effects of NMR exposure on living organisms. I. A microbial assay, *Br. J. Radiol.*, 54, 615–621, 1981.
209. Torbet, J. and Maret, G., Fibers of highly oriented Pf1 bacteriophage produced in a strong magnetic field, *J. Mol. Biol.*, 134, 843–845, 1979.
210. Trygina, G. I. and Savchuk, V. S., Effect of a magnetic field on the bacterial leaching of manganese, *Mikrobiologicheskii Zhurnal (Kiev)*,52 (3), 84–88, 1990.
211. Ueno, S. and Harada, K., Redistribution of dissolved oxygen concentration under strong DC magnetic fields, *IEEE Trans. Magn.*, 18 (6), 1704–1706, 1982.
212. Ueno, S. and Harada, K., Experimental difficulties in observing the effects of magnetic fields on biological and chemical processes, *IEEE Trans. Mag.*, 22 (5), 868–873, 1986.
213. Umanskij, D. M., Effect of magnetic field on the dielectric constant of tap water, *Zh. Teckhn. Fiz.*, 35 (12), 2245–2248, 1965.
214. Urmantsev, Yu. A., Biosymmetry. Symmetry and dissymmetry of plant florets, *Izv. Akad. Nauk SSSR, Ser. Biol.*, No. 1, 1965.
215. Urmantsev, Yu. A., Properties of D and L modifications of biological objects, *Usp. Sovr. Biol.*, no. 3, 374–389, 1966.
216. Urmantsev, Yu. A., Isomerism in livng nature. I. Theory, *Bot. Zh.*, no. 2, 153, 1970.
217. Urmantsev, Yu. A., *Symmetry of Nature and Nature of Symmetry*, 1974, Mysl', Moscow.
218. Urmantsev, Yu. A. and Smirnov, A. M., Right-handed and left-handed roots in plants, *Bot. Zh.*, 47, no. 8, 1073, 1962.
219. Ushakova, T. V., Livshits, V. A., and Kuznetsov, A. N., On the absence of the effect of magnetic field on dissolving of oxygen in aqueous solutions, *Biofizika*, 27 (5), 757–761, 1982.
220. Vadja, T., Magnetic field effect on trypsin (EC 3.4.21.4) activity, *Radiat. Environ. Biophys.*, 18 (4), 275–280, 1980.
221. Vainer, L. M., Podoplelov, A. V., Leshina, T. V., and Sagdeyev, R. Z., Effect of a magnetic field on the rate of decomposition of H_2O_2 by catalase and by the EDTA complex with Fe^{+3}, *Biofiz.*, 23, 234–241, 1978.
222. Valentinuzzi, M., Rotational diffusion in a magnetic field and its possible magnetobiological implications, in *Biological Effects of Magnetic Fields*, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 1, 63–73.
223. Valentinuzzi, M., A survey of theoretical approaches to magnetic growth inhibition, *Amer. J. Med. Electron.*, 5, 35–39, 1966.
224. Valentinuzzi, M., Ferraresi, R. W., and Vasquez, T., Behaviour of microphage cultures in homogeneous static magnetic fields, *Proc. 3rd International Biomagnetic Symposium*, University of Illinois, Chicago, 1966, 49–52.
225. Valentinuzzi, M., Ferraresi, R. W., and Vazquez, T., Culture of macrophages under homogeneous static magnetic field, *Experientia*, 22, 312, 1966.

226. Van Nostran, F. E., Reynolds, R. J., and Hedrick, H. G., Effects of a high magnetic field at different osmotic pressures and temperatures on mutliplication of *Saccharomyces cerevisiae*, *Appl. Microbiol.*, 15, 561–563, 1967.
227. Veneziano, P. P., The effect of low intensity magnetostatic fields on the growth and orientation of the early embryo of *Gallus domesticus*, *Diss. Abstr.*, 25, 4319, 1965.
228. Verkin, B. I., Bondarenko, S. I., Sheremet, V. I., Tsutsaeva, A. A., Safonova, T. S., and Yurchenko, G. G., The effect of a weak magnetic field on some bacterial species, *Mikrobiologiya*, 45 (6), 1067–1070, 1976.
229. Vogel, T. M., Criddle, C. S., and McCarty, P. L., Transformations of halogenated aliphatic compounds, *Environ. Sci. Technol.*, 21 (8), 722–736, 1987.
230. Whish, J. C., Plant growth in a steep magnetic gradient, *Biomed. Sci. Instrum.*, 1, 103–116, 1963.
231. Wiley, R. H., Cooke, S. L. J., Crawford, T. H., Fairless, B. J., Liu, H. F., and Weber, E. C., Magnetic reactivation of partially inhibited trypsin, in *Biological Effects of Magnetic Fields*, Vol. 1, Barnothy, M. F., Ed., Plenum Press, New York, 1964, 255–259.
232. Winterberg, F., Can strong magnetic fields influence the growth of cancer cells?, *Z. Naturforsch.*, 21b, 902, 1966.
233. Winterberg, F., Some theoretical considerations on the inhibition of tumor growth by ultrastrong magnetic fields, *Arch. Biochem. Biophys.*, 122, 594–598, 1967.
234. Yaw, K. E., and Kakavas, J. C., Studies on the effects of D-amino acids on *Brucella abortus*, *J. Bacteriol.*, 63, 263–268, 1952.
235. Yoder, O. C., Beamer, K. C., and Shelton, D. C., Membrane specificity of *Leuconostoe mesenteroides* for the stereoisomeric forms of glycine and valine dipeptides, *Can. J. Biochem.*, 45, 213, 1967.
236. Young, W., Magnetic field and *in situ* acetylcholinesterase in the vagal heart system, in *Biological Effects of Magnetic Fields*, Vol. 2, Barnothy, M. F., Ed., Plenum Press, New York, 1969, 79–102.
237. Zhou, H. and Liu, X., The effect of magnetic field on the growth and nitrogen fixation of *Frankia sp.*, *Acta Microbiologica Sinica*, 30 (2), 149–153, 1990.