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I. ATOMIC POLARIZATIONS

A. ORIGINS

According to Einstein special theory of relativity, the ''actors''of the fundamental duo matter — energy are interconvertible. Energy might have preceded matter and thus was there ever a time when no matter, of any sort, existed? Radiant energy could thus have preceded matter in the dualistic nature of the universe. However, and according to the widely accepted scenario (Weinberg, 1977), the radiations and matter were originally compressed in a sphere of fire; its diameter was minimal but its density and temperature were extremely high. At zero second of cosmological time, a gigantic cosmic explosion, the hot Big Bang first proposed in 1935 by the physicist Georg Gamow originated an uniform and still lasting isotropic expansion of the universe sequentially followed by the Planck time of particle creation.

In these first seconds of the universe, extremely energy rich photons (massless and chargeless weight packets of electromagnetic energy or quanta of light) would have given birth to the first elementary particles among which electrons (−) and positrons (+) forming the primeval, bipolar couple of elementary electric charges. Parallely, to these light leptons, also arose the + and − charged constituents of nuclear matter, the quarks, which associated into the heavier hadrons, proton and neutron, soon followed by the nuclei of the helium (2 protons + 2 neutrons). This radiation era of nucleosynthesis was preceded by an hadronic era of annihilation of proton-antiproton pairs and a leptonic era of annihilation of electron-positron pairs (Barrow and Silk, 1980). However, when temperature lowered, photons no longer were powerful enough to dissociate the atoms formed and every proton (H^+) became covered with an electron, forming the primordial atoms of hydrogen (H), every biprotonic nucleus of helium captured two electrons, etc. Electrically neutral atoms were thus born and the universe had passed its atomic phase.

The atomic binding between the proton and the electron is not saturated. Samples of atomic hydrogen gas could only be kept as such by exploiting the effect of spin polarization (Silvera and Walraven, 1982). The stabilized H atoms were produced by spin-polarizing all the electrons in the same direction (see I.D.4); instead of binding into pairs during a collision, they separate and H_2 will not form (Laloë and Freed, 1988). Otherwise atomic hydrogen is found strongly bonded to other elements to form chemical compound such as water, carbohydrates and other organic substances. Its ionization, when the electron escapes the electrical attraction of the proton, requires high energy as provided by electromagnetic (microwaves) radiation (quantum chaos? see Pool, 1989). Nevertheless, because of its feeble ionization in neutral H_2O (10^{-7}M H^+), the H atom provided the fundamental ion implicated in the biogenic redox reactions (see IV.B.2c).

Hydrogen as a gas made up of isolated atoms is not stable in the conditions that prevail on the surface of the earth and the atoms combine explosively to form the diatomic molecule of hydrogen (H_2) in which the two charged particles are maintained by electromagnetic forces. The two electrons can now circulate on complex orbitals around the two adjacent protons (McWeeney, 1986) and the hydrogen molecule formed is then a closed system with increased stability. The H-H molecule vibrates on a time scale of femto-second (10^{-12}s) and when a H atom approaches the H_2 molecule, to form a transition state (Eyring, 1936, see Żewail, 1988), the three hydrogens of the H_3 species transitorily formed "stick" together for about 10 fs (Zewail, 1988).

B. Symmetry - Polarity

In nuclear physics, the most basic information pertains to symmetry properties, and one of the first things any worker in the polarization field learns is the effect of parity and time reversal invariance on the relations between measurable polarization parameters, such as those between polarization and asymmetry (Barshall, 1975).

There is a long history of the study of symmetry principles in physical systems (Elliott and Dawber, 1979; Lee, 1988). In one of its aspects, it concerns the three dimensional rotational symmetries of atoms and molecules, and the translational and rotational symmetries of crystal lattices. Otherwise, the more abstract symmetries are associated with the internal structure of elementary particles and extend the familiar concept of electric charge (see I.C.1).

The principle of symmetry is satisfied when two different qualities are equivalent, as in the complementary "couple" matter/antimatter: charge symmetry implies that the antiworld with opposite charges is equivalent to ours (Weisskopf, 1969).

Under the combined inversion of charge and parity, the mirror image of any observed phenomenon represents the corresponding phenomenon, with each particle replaced by its corresponding antiparticle. This idea of antiparticle arose from Dirac (1929-30, see Davies 1980) who made the bold suggestion that perhaps there are really two types of matter: ordinary particles like electrons, and "mirror" particles of antimatter. To each particle should correspond an antiparticle endowed with an equal mass but an opposite electrical charge: the matter atom of H is formed of a positive proton plus a negative electron while the antimatter anti H is formed of a negative antiproton plus a positive antielectron or positron (von Egidy, 1987).

The level of particle-antiparticle asymmetry in the universe, which determines the entropy, is not absolutely invariant. It occurred after the early instants of the universe, when the decay processes of protons were abundant (Weinberg, 1981). A stable level of asymmetry between particles and antiparticles was eventually frozen and the predicted value became close to the observed asymmetry of one part in 10^8 (Barrow and Silk, 1980). Complex processes involved the non-conservation of the symmetry of particles and anti-particles and generated a sharp unbalance between matter and anti-matter; they erased any memory of the initial entropy per nucleon (Georgi, 1981).

It is expected that an antiworld would look essentially like ours, but with opposite electric charges. If all properties of particles and antiparticles are completely symmetric the question therefore arises as to "why our world is made of particles and not of antiparticles, and what happened after the Big Bang, so that only matter survived ?" (von Egidy, 1987).

The fact that the so-called "weak force", the fourth of the basic forces in nature along with the strong, electromagnetic and gravitational forces, shows important left-hand — right-hand asymmetries (chirality, see II.D) could be an answer to the universe's option for a lopsided, matter-dominated arrangement.

C. Electric bipolarization

An external electric field can induce a slight relative shift of positive and negative electric charges in opposite directions within an insulator, or dielectric. In all atoms, electric polarization can be provoked by an electric field which distorts the negative cloud of electrons around positive nuclei in a direction opposite the field. The slight separation of charges makes one side of the atom somewhat positive and the opposite somewhat negative. The electric field has thus induced an electric dipole moment in the atom which can then be considered as polarizable.

1) *Electric charges*

According to the standard model of elementary processes, all matter is made up of hadrons — protons/neutrons — components (quarks) and leptons (electrons, neutrinos, muons, etc.), which interact with one another through four forces: gravity, electromagnetism, the weak force and the strong force. Recently, the still undiscovered Higgs boson has been introduced to make that standard model mathematically consistent (Veltman, 1986). Electromagnetism which is the best described of these four forces that govern the interactions of matter and energy accounts for the quantization of electric charge, i.e. that charge always comes in discrete multiples of a fundamental smallest charge (Georgi, 1981).

Interconversions can occur among hadrons: a neutron can become a proton (+), emitting an electron (−) called a β-particle, while a proton can also turn into a neutron, emitting a positron — a positively charged particle that can then combine with an electron to produce γ-rays.

As prototype of the leptons, the electron has a small mass and one unit of electric charge considered by convention as negative. Muons can also carry a negative electric charge and have properties quite similar to those of the electrons even though they are much more massive. Contrarily to the leptons, which are free particles, the quarks are only constituents of heavier particles, the hadrons. In their allowed combinations the fractional electric charges of the quark add to yield an integral total charge. The *u* quarks have a charge of $+2/3$ while the charge of the *d* quarks is $-1/3$. The charged proton has the quark composition *uud* thus giving it a total electric charge of $+1$. That positive electric charge carried by the proton is equal in magnitude but opposite in sign to that of the 1,820 times lighter electron. The quarks in a proton or a neutron are thought to be held together by a new long-range fundamental force called the color force which acts on the quarks because they bear a new kind of charge called color (Harari, 1983).

Unionized atoms are electrically neutral because the negative charges on the electrons precisely balance the positive charges on the nuclear protons (Georgi, 1981). However, this deeply-rooted concept of balancing is worth a second thought: why should electrons and protons which seem to be independent forms of matter know so precisely the magnitude of each other's electrical charge?

An answer that has suggested itself to many is that ultimately there is but one type of matter: electrons and protons are siblings. If so, this would be the culmination of a long search for an underlying unity in nature. This startling result is a consequence of the electrical charge equality between the electrons and protons. But how sure are we that these charges are identical, and what consequences would ensue if they were different? Einstein had already suggested that the electron and proton charges (Q_e, Q_p) might not be precisely equated. In electrodynamics, and in the electroweak theory of Glasgow-Salam-Weinberg, the electric charges are even not fixed: proton and electron could have arbitrary charges. The reason for this would lie in the mathematical group structure of the theories. Moreover, in the description of electromagnetic interactions the much searched grand unification theory would not be ruled out by a difference in electron and proton charges, albeit small (Okun *et al.,* 1984).

However, the quantization of electric charge (particle's charges are integral multiples of the proton's charge) implies the exact neutrality of the atom (see above). This means that the strength of any given electromagnetic interaction is dependent on the size of the participating charges. Its measure is the so-called electromagnetic coupling constant (Georgi, 1981). A change in the strength of the strong interaction coupling constant of only a few percent would have dramatic consequences for the inert and living matters. As small an increase as two percent would block the formation of protons out of quarks and hence the formation of hydrogen atom. Comparable decrease would make certain nuclei essential to life unstable and small changes in the electric charge of the electron would block any kind of chemistry and, by extension of biochemistry (Barrow and Silk, 1980).

2) *Electric dipoles*

In the struggling world of matter-antimatter, the electric particulate partners of the primordial, but potential bipolar couple born from energetic photons, the electron (–) and the positron (+) annihilate one another when they collide, releasing a burst of energy in the form of gamma rays.

Similarly, a proton (H^+) of an hydrogen atom (H) can decay into a positron and a neutral pi meson; the positron would subsequently encounter an electron, perhaps the electron of H, and they would annihilate each other, giving rise to γ-rays, or high-energy photons (Georgi, 1981). This decay of an hydrogen atom into pure radiation represents a conversion of matter into energy. Moreover, when an hydrogen nucleus (proton) is violently collided with a γ-ray, an electron and its antimatter partner, the positron, are created. Because they have the same mass but opposite electric charge, the particulate partners could be visualized as traces curving in opposite directions in the magnetic field of a cloud-chamber photograph (Goldman *et al.,* 1988). Thus, particles and antiparticles can be created as diverging pairs if there is enough energy available to conserve momentum and provide mass ($E = mc^2$) while when particles and antiparticles are free, they can annihilate each other in a burst of energy (Fig. 1A).

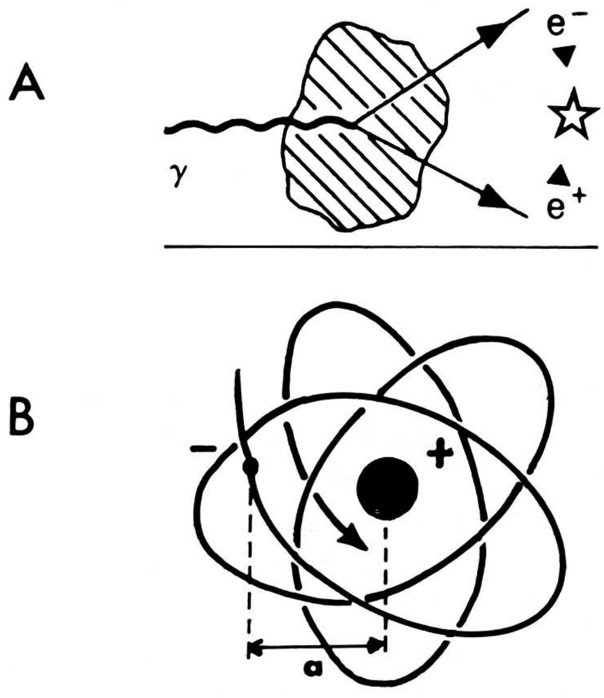

FIG. 1.

(A) Pair production of an electron ($^-$) and a positron ($^+$) by conversion of an energetic photon (γ) in the presence of an external electromagnetic field (dashed crystal); further annihilation of e^- and e^+ with energy burst (☆). Adapted from Sörensen and Uggerhoj, 1987.

(B) Multiple lemniscatic orbitals (wave functions) of the single electron ($^-$) around the proton ($^+$) of the atom of hydrogen (H). Axis (a) of the transient electric dipole probabilistically positioned.

It was only in the realm of stable matter that bipolarity could be actualized when a negative electron was matched by a positive proton, both being neutrally united — and not annihilated — into the first and simplest atom, hydrogen. In it, the single electron is randomly positioned around the unique proton according to the spin-polarized model of Einstein-Bose (Farago, 1974). Its opposite electric charges could thus remain separate by the spinning of the electron on an elliptic orbital maintaining it at distance from the central proton (Fig. 1B). This distance could be visualized as that of the first, probabilistically positioned axis of electric bipolarization.

However, how was it that the proton did not absorb the orbiting electron, leading to the decay of the hydrogen atom into a shower of photons? Puzzled by this question, Weyl suggested, in 1929 already, that the stability of matter might be explained if each kind of charge were conserved separately, the mutual annihilation of a proton and an electron being forbidden. This important question was only taken up again in 1938 by E.C.G. Stueckelberg and by Eugen P. Wigner (in a footnote) in 1949. They proposed what became the conventional views, namely that in addition to energy and electric charge there is another conserved property of matter, which has since come to be called baryon number. The baryons (from the Greek barus, heavy) are a family of particles that includes the protons and many particles heavier than the proton, such as the neutron and the highly unstable particles called hyperons. All baryons are assigned a baryon number of $+1$, and all lighter particles, including the photon, the electron, the positron, the graviton, the neutrino, the muon and the meson, have a baryon number of zero. According to the law of baryon-number conservation, the total baryon number cannot change. The decay of a proton into a collection of lighter particles would entail the conversion of a state whose baryon number is zero, and so the decay is forbidden (Weinberg, 1981).

3) *Polarized conductivity*

Electrical properties as conductivity and its reciprocal, resistivity, are responses to the stimulus of an electric field. When a voltage is applied across a semiconductor, it subjects the electrons to an electric field and causes them to accelerate. The electrical conductivity in the lattice of a semiconductor crystal of pure silicon oxide (SiO_2) can be precisely controlled by doping impurities: n-type doping is produced by freely moving electrons, for example of an arsenic atom in a silicon crystal; p-type doping of silicon by an element such as gallium, deficient in valence electrons replaced by positively charged holes. Doping of sil con semiconductors confers the desired properties of electrical conductivity acrc ss the three adjacent regions of field-effect transistors: the source, the channel anc the drain. Thus a small voltage applied to a metal gate above the channel controls the polarized flow of electrons (or of positive holes) from the source to the drain (Mayo, 1986). In the bipolar type of transistor, the electric charge is said to be applied to the base to control the flow of current between the emitter and the collector (Chaudhari, 1986).

The transistors are imprinted on semiconducting chips employed in high-speed logic operations. Chips in a computer's memory store millions of fundamental units of information, i.e. the bits, or binary digits, all equivalent to the result of a choice between two alternatives such as "yes" or "no", "on" or "off" ... and therefore + or −.

Photonic emission can also result from the abrupt change from a p-doped region (valence band) to an n-doped one (conduction band) and thus forms a diode across the p-n junction (band gap). The voltage-stimulated recombination of excited electrons in the conduction band with holes in the valence band then liberates energy as photons of laser light (Rowell, 1986).

The dipole force exerted by light on atoms can be understood by considering them to be polarizable bodies. It is often divided into two parts, the light-pressure or scattering force and the gradient or dipole force (Ashkin, 1980). The optical electric field induces an electric dipole moment in the atom and the induced dipole is acted on by the optical electric field. If the light intensity is spatially nonuniform, a force is induced parallel to the gradient of the intensity. The dipole force attracts an atom to a region of high light intensity if the frequency of the light is below the atomic resonance and repels it if it is above. Sodium atoms have also been trapped, by means of the dipole force, near the focus of a laser beam tuned below the first resonance transition (Chu *et al.*, 1986).

Electric ceramics superconductivity was discovered in 1986 by Bednorz and Müller in Cu-O perovskite-type minerals. These authors proceeded under the working hypothesis that an increase in the density of charge carriers in the materials — either in the form of electrons or positively charged "holes" — would lead to a corresponding rise in the transition temperatures (with transitions ranging from 30 to 110°K). This was found with a certain form of barium-lanthanum-copper oxide ($Ba_xLa_{2-x}CuO_4$).

Perovskites are ceramics described by the generalized formula ABX_3 corresponding to $CaTiO_3$ (calcium titanate oxides in their archetypal rare mineral perovskite). Their unit crystal cell is a cluster of polyhedrons. In the ideal form, the B cations may remain at the center of their octahedrons while in some other perovskites they are slightly shifted. The positively charged cations can thus give crystals electrical polarity: one end is positively charged and the other end is negatively charged. Moreover, the direction of the off-centering can often be changed simply by subjecting the sample to an electric field. Such perovskites thus behave as ferroelectrics that are both polarized and able to reverse polarity under the influence of an electric field. A synthetic ferroelectric perovskite $BaTiO_3$ (barium titane oxide) is widely used in electronic devices such as capacitors (smoothing out uneven flow of current) because of the "off-centering" of its cations. "The stronger the applied field, the more the cations are energized and dispersed and the more strongly polarized the crystal becomes. When the electric field is removed, the cations return slowly to their normal positions and release the stored energy"(Hazen, 1988).

If the distribution of charges in a ferroelectric-ceramic crystal is not symmetric about the crystal's center, a shift in polarization can also be produced by deforming the crystal. This is the basis of piezoelectric ceramics. When such ceramics are mechanically deformed, they develop a considerable charge; conversely, when they are subjected to an electric field they deform (Bowen, 1986).

Traditional explanations of superconductivity were based on phonon-mediated interactions with electrons (Bardeen-Cooper-Schrieffer (BCS) theory, 1957). They provided the somewhat modernized formula for the superconducting transition temperature (T_c) which makes obvious plasmons as candidates for the mediation of the electron-electron pairing.

Superconductivity has recently been explained by Anderson (1987) as based on resonating valence bonds and relying on the plasma oscillations of electrons or of holes. An alternative approach is that proposed by Mott (1987) of a bipolaron mechanism, whether single-site or not, and driven by electron-phonon coupling. Bipolarons are polarons binding in pairs which can behave as "bosons" and undergo Bose condensation into a macroscopic superconducting coherent quantum state (Emin, 1982). Otherwise, the polaron has been described as an important example of a generalized soliton in condensed matter, a notion which has been widely generalized in the past decade, especially by physicists in condensed-matter and field theory (Bishop *et al.*, 1987). An electron-induced local strain in the lattice of an unique crystal has also been referred as a "polaron" (Campbell, 1987).

In the most recently found bismuth oxide (Bi_{1-x}, K_x, BiO_3, Cava *et al.*, 1988) superconductivity would also be driven by a "bipolaronic" mechanism; the charge-ordered parent oxide could be regarded as a lattice ordering of bipolarons, or two-electron pairs, on alternate Bi^{5+} sites stabilized by oxygen relaxation. These electron pairs would become mobile by potassium-doping effect changing the number of bipolarons per bismuth site. This new system would be the best candidate so far for the long-sought bipolaronic limit of superconductivity (Rice, 1988).

In metallic systems, superconductivity is caused by an attractive interaction mediated by the exchange of lattice vibrational excitations (phonons) between electrons forming coherent pairs in the superconducting state (Bardeen *et al.*, 1957). Single crystals of these copper oxide (cuprate) superconductors, including those of the lanthanum (La)- and yttrium (Y)- barium (Ba)-based materials all show a strong anisotropy in the response of their transport properties to applied magnetic fields. Many have suggested that coupling of the conduction electrons to the magnetic moments in the metallic superconductors could cause the pairing of electrons essential to superconductivity. The superconductivity of metallic systems might thus arise from an essentially magnetically-induced interaction.

The electron-phonon coupling mechanism has quite recently been questioned for oxides of $YBa_2Cu_3O_7$ type. Severe constraints have also been imposed on theoretical models implicating the mode of coupling (Little, 1988). As newly proposed guidelines (Sleight, 1988) to further ascent superconductivity temperature, there are more concern with boundary between localized and delocalized electron behavior and with Cu-O sheet systems because the electrons paired with spins antiparallel (BCS theory) appear to reside mostly on oxygen.

D. MAGNETIC POLARIZATION

Magnets have fascinated man since the observation that iron is attracted to lodestone. Today highly magnetic ferro- (Fe and CrO_2) and ferrimagnetic (Fe_3O_4) materials are used in technological applications. These highly magnetic materials share common structural features such as atomic basis and orbital metal-based spin sites. On these fundaments, even molecular/organic based ferromagnets could be recently developed (Miller *et al.,* 1988).

1) *Cosmological level*

The earth magnetic field is known to be polarized. Recently evidence has been obtained for north-south changes or ''reversals'' in the polarity of this geomagnetic field. Observations of the intensity and direction of the field during the polarity transition have shown that the intensity decreases by a factor of four and the global morphology of the field becomes largely nondipolar (Jacobs, 1984). It has recently been shown that a patch of flux of opposite sign to that expected for a dipole field occurs beneath southern Africa. Attempts have recently been made (Gubbins, 1987) to answer the question of ''How can this rapid fall in dipole moment be related to secular variation of the core field ?''

Magnetic fields could be dynamically important for dense clouds and star formation as shown by Zeeman splitting in OH molecules. They are believed to dynamically decouple from the gap through processes such as ambipolar diffusion of ions through the neutral bulk of the gas. The Zeeman effect must be estimated from the difference in intensity between the right- and left-handed circularly polarized portions of the radiation (Boss, 1987). The magnetic field strength in dense molecular clouds is essential for determining to what extent magnetic fields are dynamically significant during protostellar contraction and collapse, as well as to explain the present chromospheric activity of stars.

2) *Magnetic fields*

The magnetic properties of a solid can be traced largely to the magnetic behaviour of individual electrons or groups of electrons within the solid. Every electron generates a small magnetic field like that of a bar magnet. When a lone electron is placed in a magnetic field, it is energetically favourable for the electron's magnetic field to be aligned in the same direction as the external field. If a sample of a given material contains a large number of lone electrons that do not interact with one another, then all those electrons will tend to align with any external magnetic field. This effect, which is known as paramagnetism, increases the strength of the total magnetic field within the sample.

There is an obvious analogy between ferroelectricity and ferromagnetism. Ferromagnetic compounds show a strong interaction between the atomic moments and their coupling is so intense that all dipoles are spontaneously oriented in the same direction (spontaneous magnetization of ferrite in the absence of a magnetic field). Diamagnetic compounds lose instantly their magnetization when the external magnetic field disappears while paramagnetic compounds can keep a faint one in the absence of a magnetic field.

Polarized patterns of magnetization have been applied to data-storage technologies for advanced computing. In tapes or disks, the magnetic storage of binary data essentially amounts to impressing a pattern of magnetization on a medium most commonly made of iron oxide. The pattern of magnetization is impressed on the medium as it moves under a gap simply by repeatedly reversing the flow of electric current in the inductive recording head. "Because computer-generated data are stored as a string of binary digits, the pattern of current reversals (and therefore the pattern of magnetization reversals) corresponds to a succession of 0's and 1's that constitute the individual bits of data" (Kryder, 1987). Back consideration from the alternate magnetization of binary digit to electric reversals highlights that the fundaments of advanced computing are deeply rooted in the universal +/- electric bipolarity.

3) *Magnetic monopoles*

In their aim to understand the Universe, the physicists have not only asked the major question "what is matter?" but also "what are the forces that act on it?" In their effort to answer them, they have dwelled on the interaction of particles and fields, particles producing fields which act on particles in a perpetual duet. These notions of "particles" and "fields" that is matter and force, were already at the core of Newton's theory of gravitation and Maxwell's theory of electro-magnetism. Quantum field theory then provided a theory of elemental particles consistent with Planck's quantum mechanism and based on a sophisticated unification of the notion of particle and field. Electromagnetism remains the simplest gauge theory, the generic name for a class of vector field theories. Generalizations of electromagnetism are called non-Abelian gauge theories. It is the topological solution (with non trivial boundary) of certain of these theories which has led, in 1974, to the discovery of generalized magnetic monopoles by 't Hooft and Polyakov (Hey *et al.*, 1988).

The dipolar nature of ordinary magnetic materials can readily be demonstrated with iron fillings sprinkled on a piece of paper held over a bar magnet. Cutting the magnet in half does not isolate the poles; instead two smaller bar magnets are created rather than isolated "north" and "south" poles. By comparison, when an electric dipole is made by depositing electric charges of opposite signs on the ends of an insulating rode which is then cut, two isolated electric poles are created. Such a possibility of isolating electric poles but not magnetic ones is a fundamental distinction between electricity and magnetism (Carrigan and Trower, 1983).

An example of a magnetic monopole would be an isolated pole of a bar magnet. Classically, of course, such objects are not found. Monopoles are even virtually eliminated because over a region only one trillionth the size of a proton, the Higgs field is essentially constant (Guth, 1983). Thus there is the philosophically appealing possibility that the Higgs transition is the origin of all matter and energy. The "universe", notes Guth, "could be the ultimate free lunch".

According to Okun *et al.* (1984), if the theory of grand unification [SU(5)] of the four forces in the universe is correct and the Higgs field (scalar bosons) does exist, magnetic monopoles should have been created in the first 10^{-35} second of the universe. Proponents of the Su(5) theory differ over the internal composition of the monopole and over how many monopoles should exist; it is generally agreed that the monopole should have an enormous mass for an elementary particle, perhaps from 10^{16} to 10^{17} times the mass of the proton.

Although there have since been scattered reports of finding monopoles, none have yet been substantiated. As remarked by Hey *et al.* (1988) "no monopole has actually been observed neither their existence required in the standard quantum chromodynamics electroweak theory. However, they are predicted to exist in more ambitious "grand unified" theories that incorporate the color and electroweak gauge groups into a larger gauge group although the density of such monopoles in the universe may be so low as to make their detection quite unlikely."

4) *Spin polarizations*

Since 1925, it is known that every electron has a property called spin which became an important element in the development of quantum mechanics and atomic physics, particularly in the work of P.A.M. Dirac. A spin is the quantum number of electron. It makes this particle behave like a bar magnet, giving it a magnetic moment (Fig. 2A). Unlike the spin of a ball the spin of an atom or a subatomic particle is therefore quantized.

The magnitude of the spin can assume only integer or half-integer values and the vector can have only a finite number of directions. The hydrogen atom has integer value (1) of spin and belongs therefore, as the photon (0) to the boson class of particles. However hydrogen is a composite boson and its contituents proton and

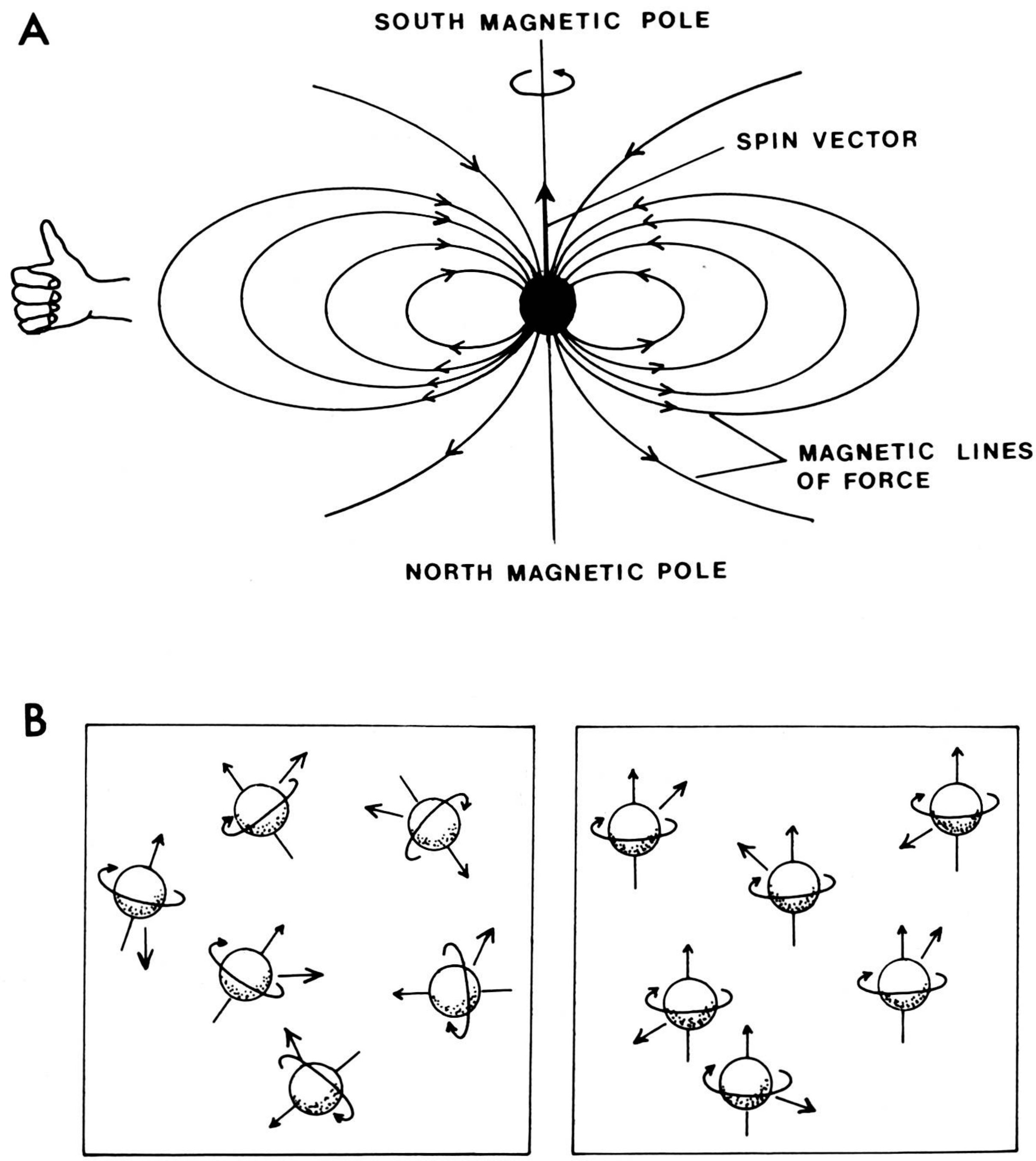

FIG. 2.

(A) Spin angular momentum of a particle with both mass and spin generating a magnetic field. For a negatively charged particle such as the electron the magnetic north pole points in the direction opposite to that of the spin vector (right thumb pointed in that direction). Redrawn from Fig. in I. F. Silvera and J. Walraven, Scientific American, vol. 246 (1), p. 58 (1982), with authorization.

(B) *Left:* gas of unpolarized atoms, with their spins pointing in all directions. *Right:* spin-polarized atomic nuclei, with their spins, or spin angular momenta, aligned in the same direction (arrows pointing up). Redrawn from Fig. in F. Laloë and J. H. Freed, Scientific American, vol. 258 (4), p. 70 (1988), with authorization.

electron which have half-integer value of spin (1/2) are fermions (Silvera and Walraven, 1982). Contrarily to bosons, fermions obey the quantum mechanical rule called the Pauli exclusion principle. According to this principle, two fermions (electrons, protons, neutrons) cannot occupy the same orbit if they have identical quantum numbers.

The scattering of spin-polarized electrons by spin-polarized "one electron" atoms (such as hydrogen or the alkali atoms) can be described as follows: the spin polarization of the electrons and atoms is denoted by specifying the direction of the spin orientation as parallel or antiparallel to an arbitrary axis of quantization. The spin vector can thus point in one of two directions, either "up" or "down". For instance, the two electrons of a helium atom have antiparallel spins and so the magnetic moments cancel. In paronic helium, however, the spins are parallel and the magnetic moments add up (Fig. 2B). Thus each atomic orbit — in succession at progressively higher levels — can accomodate up to two electrons as long as their spins point in opposite directions. However, the Pauli principle could be violated in rare "paronic" states in which two identical fermions would occupy a state simultaneously; one of the orbits would be filled by two electrons whose spins are parallel (Greenberg and Mohapatra, 1987).

All the building blocks of matter — electrons, neutrons, protons and nuclei — seem to be spinning like tops. The spinning is a basic quantum-mechanical property: each particle has a definite amount of spin, or spin angular momentum, just as it has a definite mass and a definite electric charge. "When two spinning particles collide, the direction of their spin can affect how they scatter, just as the "english" on billiard balls can alter their rebound after collision" (Krisch, 1987).

Spin is an intrinsic property of every particle. In general, it is composite since every atom is a composite entity consisting of a nucleus and one or more electrons. Thus, and according to quantum theory, the nucleus has spin, or spin angular momentum, namely it rotates like a top about its axis. As the electron and the nucleus of the hydrogen atoms are both polarized, these atoms can be considered "doubly polarized" (Laloë and Freed, 1988). Their nuclear spins can be either parallel or antiparallel with respect to the spins of the polarized electrons. Molecular hydrogen can therefore only gradually form when atoms with antiparallel nuclear spins become slightly depolarized and thus can recombine with one another (Silvera and Walraven, 1982).

The properties (viscosity, heat conductivity, etc,) of the spin-polarized gas of atoms produced are markedly changed. This leaves open the puzzling question of "how can nuclear spins, which are so weakly coupled to the outside world, so dramatically change the macroscopic properties of a gas ?" (Laloë and Freed, 1988). Spin waves is another spin phenomenon occurring in a polarized gas. It is "a collective oscillatory mode of the nuclear spins, so that the spins process, or rotate, about the average direction of polarization at a frequency that depends on the amount of polarization'' (Laloë and Freed, 1988).

Polarized beams of particles (protons, deuterons and even tritons) are produced by existing polarized ion sources and used as targets in nuclear physics experiments (Krisch, 1987). They are useful to study either the spin-orbit or the spin-spin interaction. In describing the elastic scattering of these polarized particles the observed angular distribution is usually fitted with an optical potential which must contain a spin-orbit term if it is to yield polarizations (Barshall, 1975).

Like all spinning charged bodies, the electron has a certain amount of spin and therefore creates a magnetic field; in some ways the electron can be thought of as a tiny bar magnet. In most stable compounds all the electrons form pairs in which the magnetic fields of the two electrons are aligned in exactly opposite directions. In some molecules, however, there is an unpaired electron. In electron-spin-resonance spectroscopy the investigator gauges how the energy of such unpaired electrons changes in a rapidly varying magnetic field. The results provide clues to the molecular environment of the unpaired electrons (Youvan and Marrs, 1987).

One extremely powerful method to answer questions about molecular structure is nuclear magnetic resonance (NMR). This spectroscopic technique relies on the fact that atomic nuclei with an odd number of nucleons (protons and neutrons) have an intrinsic magnetism that makes each such nucleus a magnetic dipole, in essence a bar magnet. Two fields are applied to cells or any other part of a living organism. The first is a strong magnetic field which causes the nuclear dipoles (H_1, C_{13} and P_{31} nuclei) to orient themselves so that the dipole of each nucleus is aligned either with the field (low energy) or against it (higher energy). The second field applied consists of electromagnetic radiation in the radio-frequency part of the spectrum. With the magnetic field strength held constant and the radio frequency varied leads sometime to the resonance of the nuclei absorbing the radio photons (Shulman, 1983).

By probing the electronic environment of the cations in an electride — ionic salts behaving as anions, the simplest anion being the electron (Dye and DeBacker, 1987) — nuclear magnetic resonance can also reveal how much time the trapped electrons spend near a cation. Lone trapped electrons are paramagnetic — their magnetic fields become aligned with any external field — and so the magnetic field of such an electron near a nucleus will add to external field to produce a greater total magnetic field in the vicinity of the nucleus.

E. Light polarization

The photon is a quantum of light or electromagnetic radiation. It is a massless particle that has no electric charge of its own and that moves (by definition) with the speed of light. The wavelength of the photon is inversely proportional to its energy, so that the photons associated with radiation of short wavelength such as blue light are more energetic than "red" photons. The highly energetic "blue" photon is therefore the most efficient to remove an outer electron from an atom (resonance ionization spectroscopy).

In quantum electrodynamics, the photon is therefore the intermediary particle which is exchanged at the interaction of two charged particles, such as two electrons. The explanation of this peculiar properties of the virtual photon lies in the uncertainty principle introduced into quantum mechanics by Werner Heisenberg. The uncertainty principle does not invalidate the conservation laws of energy and of momentum, but does allow a violation of the laws to go unnoticed if it is rectified quickly enough.

Energetic photons may convert into electron-positron pairs, but only in the presence of an external electromagnetic field — a process called pair production (Fig. 1A). The basic mechanism responsible for that conversion of a photon into a particle-antiparticle pair is identical to that enabling a charged particle moving in an external field to emit electromagnetic radiation (Sörensen and Uggerhoj, 1987).

Polarization of the photon — the direction of its associated electric field — is, with its intrinsic spin, an important parameter characterizing quantum waves. Phase shifts in these quantum waves have recently been reported to be caused by varying the polarization state of the photons in split laser beams (Rowell, 1986). In Maxwell's theory of electromagnetism photons transmit forces between other particles. The quantum state of a pair of photons is the state in which both photons are linearly polarized along a vertical axis. Another possible state is the one in which they are both linearly polarized along a horizontal axis.

A photon can exist in ambiguous state until measurement is made. If a particle-like property is measured, the photon behaves like a particle and if a wave-like property is measured, the photon behaves like a wave. Whether the photon is wave- or particle-like is indefinite until the experimental arrangement is specified. The quantum state of the photon is fixed if three quantities are known: the photon's direction, its frequency and its linear polarization (the direction of the electric field associated with the photon).

Because the wavelength of γ-rays is very short (about 10^{14} m at 100 MeV), classical wave technique cannot be used to measure their polarization. The kinematics of the particles produced by the interactions of γ-ray photons (Compton scattering and "pair production") can be used, however. The emerging particles (electrons or electron-positron pairs) have azimuthal distribution related to the plane of the electric vector (polarization) of the incident γ-ray (Dean, 1987).

Natural light with its electromagnetic wave lengths in the visible spectrum can also be polarized. Directed through Nicol prisms of Islandic spath (calcite crystals) or thin "polaroid" filters, light is no longer propagated along all axes covering 360° of a plane perpendicular to light direction but only along a privileged plane called polarization plane. Light can be polarized in three ways: when the oscillating electric fields of the beam are directed left and right in the plane of the page the light is said to be horizontally polarized; if the electric fields are directed up and down in the plane of the page, the beam is vertically polarized; if the field direction moves like a circle, the light is said to be circularly polarized. Either calcite crystals or piles of glass plates can serve as the polarization analyzers, since each of them is much more efficient than an actual polarizing film in blocking photons polarized perpendicularly to the transmission axis (Shimony, 1988).

Many molecules important in plants and other living things will, in solution, rotate the plane of polarization of a beam of polarized light. These optically active molecules or enantiomorphs (see II.D) typically contain at least one asymmetric carbon atom (an atom with four different groups attached to it). In many arthropods, polarization vision is thought to be based on the rhabdomere structure of their compound eyes. The regular closely packed microvilli of rhabdomeres run in a single direction only and perpendicular to the lozenge long axis, suggesting that they operate as polarization analyzers (Marshall, 1988).