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Electroweak Analogue of the Stern-Gerlach Effect: Parity Conservation Restored?

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Abstract:

The history of the longitudinal polarization experiments carried out by Wu et al, in 1957 is reviewed. It is pointed out that the conclusion that these results are an indication of parity non-conservation in weak decays rests on a key assumption, namely that the electron and neutrino are created in the decay and are not present in the nucleus beforehand. Calculations employing the exponentially damped Breit-Pauli Hamiltonian have shown that is possible to bind an electron in the neutron strongly enough to overcome the high kinetic energy required to keep it in the small volume of the nucleus, contrary to the widespread belief to the contrary promulgated by Fermi and co-workers. On the basis of the combined electroweak interaction, it is reasonable to expect that something akin to the magnetic Stern-Gerlach effect might be operative in such decay processes. In this case, in-homogenous fields can be expected to have a dominant effect on the spins of the decay particles. The field gradient should be positive, i.e. increasing in the direction of the field, at the onset of the decay for the lightest particles and therefore determine whether the momentum of the antineutrino is parallel or antiparallel to its spin. Based on this assumption, one arrives in a straightforward way at the conclusion that anti-neutrinos will always behave as right-handed screws in weak decays and neutrinos as left-handed screws. Similar effects are expected for positrons and electrons, respectively, but only with partial polarization governed by their v/c ratios in the decays. Other heavier particles such as the proton and muon simply react to the motion of the lighter particles so as to satisfy the conservation laws of energy and linear and angular momentum. The resulting dynamical interpretation of the weak decays thus avoids the conclusion that parity is not conserved in all interactions.

Keywords:

Electroweak Interaction, Longitudinal Polarization, Stern-Gerlach Effect, Two-component Theory of the Neutrino

1. Introduction

The belief that the electron and neutrino are not present in the neutron prior to its spontaneous decay has recently been called into question on the basis of quantum mechanical calculations [1]. The longitudinal polarization experiments that were carried out in 1957 by Wu et. al. [2] led to the conclusion that parity is not conserved in the weak interaction which is responsible for the decay of the neutron and other nuclei. This surprising result had been predicted earlier by Yang and Lee [3] on the basis of their speculation concerning the so-called tau-theta puzzle in particle physics. It led to what has been referred to as the two-component theory of the neutrino, whereby it is claimed that neutrinos always behave as left-handed screws in weak decays whereas antineutrinos always behave as right-handed screws.

The question that will be considered below is whether it is possible to explain the results of the longitudinal polarization experiments in a convincing manner without violating the longstanding law of the conservation of parity. To this end, attention will be directed to the more basic question of whether the particles which are invariably emitted upon weak interaction decay processes are simply created at the time of decay or whether instead they actually exist in the nucleus prior to their detection.

2. Longitudinal Polarization and Parity Conservation

In Sect. 3 of Ref. [1], the phenomenon of longitudinal polarization of the emitted particles in β-decay processes was briefly mentioned. In the period immediately following the first such experiments [2], physicists quickly had to come to grips with the surprising thesis that parity is not conserved in the weak interaction. This proposal had first been made by Lee and Yang [3] in 1956. The original motivation for their hypothesis was the observation [4] of two seemingly identical particles, then tentatively referred to as τ and Θ, which nonetheless were thought to decay differently from one another. As mentioned in Ref. [1], since the evidence from nuclear and atomic-molecular processes was consistent with the view that parity is conserved in all physical interactions, the assertion that this state of affairs does not hold generally was first met with considerable scepticism.

The experiments of Wu et al. [2], carried out in response to the suggestion of Yang and Lee and fulfilling their expectations in a spectacular manner, changed this view dramatically, however. The situation is perhaps best illustrated by a letter [5] written by Pauli shortly after being confronted with this experimental evidence. The theoretician who had prevented the discarding of the conservation of energy principle [6] in interpreting the results of β decay by postulating instead the existence of a previously unknown particle [7], the neutrino ν, was now put in the position of having to accept the fall of an equally cherished law of nature, the conservation of parity. When we examine the theoretical arguments which ultimately led to this development, however, we find that an important assumption of a different kind is also involved, one which has been at issue from previous work [8], namely the hypothesis of the creation and annihilation of matter. It is therefore interesting to review the key experimental observations with special emphasis on this aspect of the theoretical description.

The ^{60}Co β decay studied by Wu et al. [2] involves the Gamov-Teller selection rule [9], $\Delta J=\pm1$, which makes the experimental verification of the longitudinal polarization of the emitted particles somewhat easier to follow. Since the experiment is carried out at an initial temperature of only 0.01° K in the presence of a strong magnetic field, the J=5, M_J=5 state of ^{60}Co is populated almost exclusively prior to decay, from which the J=4, M_J=4 ^{60}Ni state must be formed in view of the above selection rules. Conservation of angular momentum thus requires that the emitted electron and antineutrino both have α spin, i.e. pointing in the same direction as that of the product nucleus. Since electrons are *observed to exit predominantly in the direction opposite to that of the external magnetic field,* the hypothesized polarization effect is clearly demonstrated by this experiment. The polarization is not complete, but it is found to be of the highest degree that can be expected when account is taken of the fact that the electron's velocity is less than the speed of light. As Wu recounted in a review article [10] "… viewed from the position of the emitted beta particles, the nuclei ^{60}Co appear to rotate clockwise; left can be distinguished from right, therefore, parity is *not* always conserved, as shown by this experiment; moreover, the asymmetry observed is as large as possible."

It was subsequently shown that electrons are also longitudinally polarized when they emerge from un-oriented nuclei [11,12]. By counting electrons spinning parallel ($d\lambda_+$ and antiparallel ($d\lambda_-$) to the direction of the nuclear spins the polarization P was determined as

$$P = (d\lambda_+ - d\lambda_-)/(d\lambda_+ + d\lambda_-) = -/+ v/c$$

where the upper and lower signs hold for decay electrons and positrons, respectively. The degree of polarization was demonstrated to be proportional to the particle's velocity ($v=c^2p/W$, where p and W are its momentum and energy, respectively. In addition, these experiments verified that the sign of the polarization was opposite for the anti-particle, i.e. positrons behave as right-handed screws, while electrons are more likely to be left-handed by the same margin.

The neutrino's longitudinal polarization in the weak interaction was also measured by studying the nuclear recoil in β-decays [13]. It was found that the polarization was complete within experimental error. Neutrinos were found to behave as left-handed screws, while anti-neutrinos exhibited the opposite polarization, thereby providing a clear means of distinguishing between these two charge-less particles.

Subsequent experiments [14] on the electron capture of ^{152}Eu demonstrated that the emitted neutrinos are also left-handed, and by inference that the antineutrino is right-handed. Nuclear recoil in both Gamov-Teller ($\Delta J=\pm 1$) and Fermi ($\Delta J=0$) decays consistently verify this property of neutrinos and antineutrinos [10-12]. In the ^{60}Co decay the recoil of the product nucleus is such, for example, that conservation of momentum forces the emitted antineutrinos to always exit in the direction of the applied magnetic field. This fact when combined with its α spin as deduced above leads to the conclusion that the antineutrino is characterized by positive (right-handed) helicity.

3. Assumption of A Three-Particle Neutron Composition

The thrust of the parity non-conservation argument is thus as follows. Since neutron decay takes place in free space, one must expect on the basis of assuming that parity is conserved in all interactions, β decay in particular, that there should be no preferred direction of motion relative to the nuclear spin. *An applied magnetic field can have no effect on this relationship,* because as a pseudo-vector, it is unchanged by a coordinate inversion. If a neutron is a particle without internal structure prior to its decomposition, the observed longitudinal polarization of its decay particles is therefore incompatible with parity conservation. The situation changes in a fundamental manner, however, if the original system consists of *three particles instead of one,* as suggested in Refs. [1,15,16]. Particularly if the relative orientation of the spins of these particles plays a major role in determining the stability of the initial and final systems, *it is no longer logically compelling that the longitudinal polarization observed in all β decays is inconsistent with parity conservation.*

The calculations for the $p^+e^-\bar{\nu}$ system discussed Refs. [15,16] indicate, for example, that the $e^-\bar{\nu}$ complex greatly prefers to be in a singlet state, and that the spontaneous decay comes about primarily because of a spin flip which destroys this relationship between these two light particles. The terms in the exponentially damped Breit-Pauli (XBPS) Hamiltonian [17] which are responsible for this result are the short-range Breit-Pauli interactions which at typical atomic inter-particle separations correspond to magnetic effects. The Hamiltonian itself commutes with each of the parity, charge-conjugation and time-reversal operators as well as any combination thereof, including the CPT product of the Schwinger-Pauli-Luder's theorem [18,19,20], so it cannot be claimed that there is any inherent property in the present model which could lead to a non-conservation of any of the above quantities.

Calculations with the XBPS Hamiltonian find a strong binding for the proton, electron and antineutrino in the lowest $1/2^-$ state of the combined system, which it has been argued in Ref. [16] would correspond to a (meta-stable) particle with a magnetic moment of the order of a nuclear Bohr magneton. After a spin flip occurs of the type discussed above, it can be expected that a quite different situation results, however, *in which each partic1e is strongly repelled by the same forces which hold the system together in its original meta-stable configuration.* That there might be a high correlation between the spin of each particle and its direction of motion under such circumstances is not at all implausible, in decided contrast to what must be concluded if it is assumed that the electron and antineutrino first come into existence at the time the decay process begins *and not before it.*

If we assume that strong magnetic-like fields are set loose at the time of β decay, it follows that the spins of the individual particles (and their magnetic moments) determine the strength of these forces. There is no law of conservation of magnetic fields, but the net force on the three constituent particles must be unchanged by virtue of Newton's Third Law as a result of such an internal change in the structure of the decaying system, and the same holds true for the system's total angular momentum. Since no particle is affected by a self-generated magnetic field, it follows that the resulting forces are different for each of the decaying species. For example, the antineutrino is only acted upon by the fields of the proton and electron, while the electron experiences the fields of the antineutrino and proton only. The only requirement is that the vector sum of the individual forces vanishes.

Since the exponentially-damped Breit-Pauli interactions are mainly responsible for such forces according to the calculations, it follows that the charge-to-rest-mass ratios which are the coupling constants determining the magnitudes of these effects are crucial quantities for understanding the dynamics of β decay. In the $p^+e^-\bar{\nu}$ system the absolute magnitude of the q/m_o values decreases in the order: electron, antineutrino, proton. A positive q/m_o value only about 60-70% as great in absolute magnitude as that of the electron is required to obtain the experimental neutron energy in the above calculations [15]. It is also argued therein that this choice still allows for a consistent explanation of the non-ionizing properties of neutrinos (cf Figure 1 of Ref. [15]) on the basis of the exclusively long-range repulsive character of the corresponding interactions which result from it, while at the same time providing for short-range attractive forces of the strength required to form a suitable $e^- \bar{\nu}$ complex with which to bind protons in nuclei.

On the basis of these considerations an interesting series of correlations can be identified between various theoretical and experimental properties related to the longitudinal polarization phenomenon. For example, the q/m_o values for e^+ and $\bar{\nu}$ are positive, just as are their helicities. Charge conjugation changes the sign of these q/m_o ratios, giving them negative values for e^- and ν, which is also the sign of their helicities. In terms of the Breit-Pauli interactions the correlation becomes even more striking, namely *the magnetic moments of each of the four particles above point in the same direction as their momentum vector in β decay.* After taking account of the v/c factor in the polarization function [10-14], one can summarize all known experiments dealing with this phenomenon as follows (Figure 1): the emitted electrons and neutrinos and/or their antiparticles always show a strong preference *for orienting their magnetic moments parallel to and in the same direction as the forces acting on them after β decay occurs.*

In any conventional system subjected to a strong magnetic field, it can be expected that the constituents with the largest magnetic moments will show the strongest reaction in order to minimize the total energy, so the direction of the accompanying force can be deduced most simply by observing their behaviour. The above correlation is perfectly consistent with such a pattern. The lighter components of the neutron or other β-decaying system orient themselves with a definite preference. The importance of the v/c ratio also fits in with such observations, since the velocity of the emitted electrons is clearly a good indicator of the strength of the forces to which they are subjected, and their tendency to orient themselves in the magnetic field depends very much on this factor. Since the net force on the nucleus must be zero as a whole because no external interactions are present, it is also clear that not every constituent is free to alter its spin direction so as to have its magnetic moment parallel to the magnetic field.

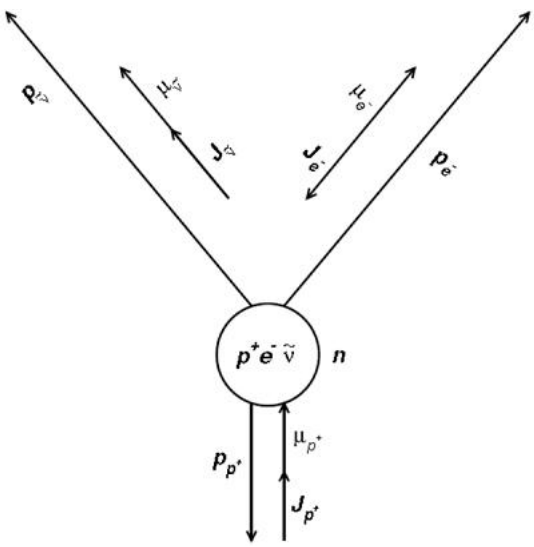

Figure 1. *Schematic diagram.*

Figure 1 Schematic diagram showing the relationship between the linear P_i and total angular J_i momenta of the particles emitted upon the β decay of a neutron. The magnetic moment $\mu_i = (q_i/2m_{oi})\ J_i$ of the electron and antineutrino is observed to point in the same direction as its momentum vector P_i, thus giving rise to the phenomenon of longitudinal polarization. The corresponding proton quantities (with by far the smallest $|q/m_o|$ value of the three decay particles) must point in opposite directions in order to satisfy the conservation laws for linear and angular momentum for the system as a whole. If all three particles are assumed to be present in the neutron prior to decay, it is possible to explain this behavior in terms of inhomogeneous magnetic-like fields which arise as a result of a non-radiative transition (spin flip), rather than as a violation of the law of parity conservation.

As a result, the behaviour of the heavier particles in the weak interaction is inevitably more determined by momentum conservation laws than by any magnetic preferences of its own. Thus, the positive muon must leave a decaying pion with the opposite spin and velocity direction as the associated neutrino [21,22,23]. Consequently, since a neutrino has negative helicity, so must the positive muon as well. We thus have a system (μ^+) which has a magnetic moment with a sign opposite to that of its helicity. This behavior is exactly what must be expected when one realizes the $|q/m_o|$ value of the neutrino is much larger than that of its heavier counterpart. It therefore has more to gain by orienting its spin in a particular direction than does the muon. Similarly, the proton also exhibits a negative helicity [14,24] in β decay, i.e. of opposite sign to its magnetic moment. This is clearly seen in Fermi ($\Delta J = 0$) interactions for which both electron and antineutrino must depart in the same direction with opposing spins. Under these circumstances the proton must recoil in the opposite direction. The experimental results indicate that the $\bar{\nu}$ spin is almost always parallel (with a 5/6 probablity) to that of the decaying neutron, so the proton spin must be opposite to that of the electron (and thus parallel to that of the antineutrino) to ensure doublet multiplicity for the system as a whole. If on the other hand, the electron and anti-neutrino were *created* in a state with S=0, there would be equal probability that the neutron and $\bar{\nu}$ spins would be anti-parallel, contrary to the experimental data. Again, the proton can be looked upon as simply reacting to the magnetic behaviour of the lighter particles, and therefore foregoing its tendency in the isolated state to align its magnetic moment in the same direction as its momentum [25]. In summary, the lighter particles behave in the weak interaction as if they strongly prefer to orient their magnetic moments in the direction of the respective field acting on each of them (Figure 1), while the behaviour of all other (heavier) particles in the same processes can be understood on the basis of the consequences of the conservation laws for linear and angular momentum.

The occurrence of longitudinal polarization in pion and muon decays is also discussed in detail in Sect. V of Ref. [25]. It is therein concluded that "*the pion decay studies do not really tell us anything about the intrinsic helicity of the muon, demonstrating only that ν_μ, like ν_e, is left-handed and fully polarized in such experiments.*" The muon decay process is more complicated since it produces three particles (e^+, $\bar{\nu}_\mu$ and ν_e). After detailed consideration of the spin relationships, it is concluded [25] that "it appears that the motion of the neutrinos determines the nature of the longitudinal polarization effects observed for the heavier particles involved in weak decays."

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4. Possible Relationship With the Stern-Gerlach Effect

There is another key point which needs to be taken into account in attempting to rationalize the observed correlation between magnetic moments of particles and the direction of their motion. A homogenous magnetic field does not impart a net force on a magnet. Instead, only a torque is applied which tends to orient the magnetic moment of the system in the direction of the field. Since the particles in β decay depart with high energy, it is clear that the corresponding fields acting upon each of them cannot be homogenous, but such a property is hardly surprising in view of the spin-flip mechanism in the above model, which causes a rapid reorganization of the magnetic forces.

In the Stern-Gerlach experiment, an inhomogeneous *magnetic* field imparts a net force on an electron or other particle which deflects it in a given direction, depending on the sign of the magnetic moment μ and that of the field gradient. If the **B** field is in the z direction, $E = \mu_z B_z$ and the component of force in the same direction is given by $F_z = \mu_z\ \partial B_z/\partial z$. This means that *if the gradient is positive* in the direction of the magnetic field, i.e. $\partial B_z/\partial z>0$, the direction of the force must be the same as that of the magnetic moment component μ_z.

Since electrons and neutrinos prefer to move with their magnetic moments in the same direction as their momenta in β decay, the above arguments indicate that the relevant field gradient would have to be positive in the field direction for each particle *at the time immediately following the radiation-less transition.* The key point is that such a field is generated by the spontaneous decay of the nucleus. It is distinct from an ordinary magnetic field, in other words. To this end, it will be given a name, namely **BE**, which makes clear that it is electroweak in character and is not to be confused with a magnetic field. Moreover, it will be helpful to specify the particle on which the field acts, for example, by including the particle name in parentheses. Thus, for the neutrino the corresponding field will be denoted **BE** (ν). It is directed outward from the nucleus along the z axis of the specific coordinate system used to describe this interaction. The force applied to the neutrino is therefore denoted $F_z(\nu) = \mu_z(\nu)\ \partial BE_z(\nu)/\partial z$, in order to make the analogy with the magnetic Stern-Gerlach effect as transparent as possible. The sign of $\boldsymbol{\mu}_z(\nu)$ is clearly critical in the ensuing analysis. It determines whether the electroweak magnetic moment is parallel or anti-parallel to the spin of the particle. The experimental data indicate that this sign is negative for both the electron and neutrino and positive for each of their respective antiparticles.

The example of the neutron decay in Fig. 1 serves as a useful illustration of the above interaction. It is modelled after the Fermi decay with ΔJ=0 in which the antineutrino emerges with α spin while the electron has β spin. In the case of the antineutrino, this means that the sign of the magnetic moment $\boldsymbol{\mu}\bar{\nu}$ is positive and therefore that it points in the same direction as its spin $\mathbf{J}\bar{\nu}$. As the particle with the smallest rest mass it is assumed that the electroweak field gradient $\partial BE_z(\bar{\nu})/\partial_z$ is positive at the onset of the transition. Accordingly, the force also points along the positive z axis, and therefore one expects the antineutrino to be ejected in the forward direction as shown in the figure. Note, however, that if the spin direction is changed by for example inverting the magnetic field in the longitudinal polarization experiment, the result would be that the direction of $\boldsymbol{\mu}\bar{\nu}$ is also changed. Inverting the magnetic field has no effect on the electroweak field, however, so one expects from the electroweak Stern-Gerlach analogue that the force and therefore the momentum $\mathbf{P}\bar{\nu}$ direction are changed as well. As a result, the spin and momentum vectors would both still lie in the same direction, and the helicity of the antineutrino would have the same value as before the change in magnetic field occurred.

Nonetheless, it is still possible to imagine another set of experimental conditions in which the antineutrino would be found to behave as a left-handed screw. This is not possible in the present example because it is assumed that the field gradient $\partial BE_z(\bar{\nu})/\partial z$ would inevitably be *positive at such an early stage in the decay*. In other words, it is not necessary to assume a unique characteristic for the antineutrino in order to explain its exclusively positive helicity in the Fermi decay process. A completely similar analysis can be made for the Gamov-Teller decays. The same conclusion holds for the decays of un-oriented nuclei. The salient point in all these cases is that the sign of the electroweak field gradient must be expected to be positive at the time that the field acts on such a mass-less particle. If this were not the case, a left-handed antineutrino would be possible and there is no reason to expect that this relationship cannot exist in other types of natural processes.

The emission characteristics of the electron in the Gamov-Teller decay [2], in which case both the electron and antineutrino have α spin, can be explained in a very similar way. One only needs to assume that there is a reasonable chance that the corresponding field gradient $\partial BE_z(e^-)/\partial z$ will be *positive* at the time of the electron's ejection from the nucleus. The likelihood of having a negative value for the field gradient at this time increases with the elapsed time subsequent to the moment of spontaneous decay. This possibility can be the reason for the v/c factor in the electron counting rate [11,12,13,14]. If the field gradient is still positive at the time of emission, it is expected that, since the magnetic moment $\boldsymbol{\mu}_e$ points in the opposite direction as $\mathbf{BE}(e^-)$, the momentum $\mathbf{P}_e$ will also point in that direction. In that case, it is seen that $\mathbf{J}_e$ (α spin) and $\mathbf{P}_e$ are anti-parallel and that the predominant helicity for the electron value is -1, as is observed.

The fact that the electron has α spin is a consequence of the presence of a magnetic field. Reversing the direction of the magnetic field changes the value of the spin to β, which in turn also changes the direction of $\boldsymbol{\mu}_e$. As a consequence of the analogue of the Stern-Gerlach effect, i.e. because the sign of $\partial BE_z(e^-)/\partial z$ remains constant, this means that the electron momentum also changes direction. Therefore, the helicity of the electron is unchanged, i.e. $\mathbf{J}_e$ and $\mathbf{P}_e$ remain anti-parallel to one another. This shows up in the experiment by the reversal in the electron counting rate. The preference is still for the decay electrons to be detected more in the backward direction to the applied magnetic field (and nuclear spin) than the forward.

While it is difficult to be certain about such details, the above set of circumstances does make such an arrangement seem at least plausible. If it were possible to observe one of the lighter particles from down field at the start of the decay, it is reasonable to expect that the field strength acting on it would increase monotonically as it is approached more closely. For the gradient to be positive at the location of the particle itself would mean that there is a type of inertial effect according to which the field's build-up would not stop until some later point in time. The larger this effect, the greater the force that would be imparted to the particle and the greater the tendency for a system with a large $|q/m_o|$ ratio to orient its magnetic moment along the field direction in which it departs. That would mean positive helicity for positrons and antineutrinos, and negative helicity for electrons and neutrinos, exactly as observed.

The point of the above arguments is not to insist that specific conditions caused by damped Breit-Pauli. interactions must occur exactly as speculated above. Rather, it is to show that once one assumes that the neutron is a system with a tri-atomic composition ($p^+e^-\bar{\nu}$) *prior to its decay,* it is no longer necessary to assume that the pertinent Hamiltonian must fail to commute with the parity and/or charge-conjugation operations to produce the type of correlations observed experimentally between the respective spin and momentum directions of β decay fragments. In other words, *there is no reason to be certain that parity is not conserved in the weak interaction once one gives up the idea that only a single partic1e with no internal components is present prior to decay.*

The same observations can be taken as strong evidence that: a) the electron and antineutrino do exist as components of the neutron or of an associated bound nucleus, and b) the forces which bind them together (and overcome the high kinetic energies required by such close confinement) are very much dependent on the spin orientations of the individual particles both before and after the decay process occurs. It can also be noted that the analysis of multiplet structure in the nuclear-shell model of Goeppert-Mayer [26] and Jensen [27] is quite consistent with the second of these points, indicating that strong spin-orbit and related effects of Breit-Pauli type are needed to explain the observed systematics in electromagnetic and other properties of such systems.

Viewed in this manner it is possible to draw a parallel between the longitudinal polarization phenomenon and another effect which proved to be crucial in the development of the theory of molecular structure. For many years there was considerable uncertainty over the question of whether an electrolyte such as NaCl is best looked upon as a neutral diatomic molecule or as a pair of oppositely charged atomic ions. It was known that melts of sodium chloride and other salts could be electrolyzed to give the respective positive and negative ions, but since a substance such as water was thought to consist of molecules even though it can be decomposed by electrolysis into ions as well, this characteristic was not deemed sufficient in itself to settle the issue. The study of the colligative properties of solvents (vapor pressure, melting and boiling points and osmotic pressure) ultimately did produce clarity [28], however, since a system such as NaCl was found to exhibit nearly double the effect per gram-mole of solute as any of a large series of non-electrolytes. This result showed that the individual ions in NaCl enjoy nearly the same freedom of movement in the condensed phase as do single molecules of non-polar substances.

By analogy, the question raised in the present analysis is whether a neutron always behaves as a single unit up to the point at which it undergoes decay. The only way to answer this question affirmatively based on the longitudinal polarization results is to discard the law of parity conservation in the weak interaction. As soon as one leaves open the possibility that the neutron is a meta-stable complex of three different elemental particles, however, such a conclusion is no longer the only alternative. Instead, one can turn the argument around and say, *because parity must be conserved,* there is no recourse but to assume that the neutron does contain several component particles before decay, and therefore that *they are not merely created at the time the decomposition process begins.* The construction of a Hamiltonian which is capable of describing the binding of protons, electrons and antineutrinos within the small dimensions of a nucleus gives credence to the latter interpretation, and thereby raises the possibility that parity, charge conjugation and time reversal, just as energy, linear and angular momentum, are all perfectly conserved in β decay, as well as in all other physical processes which have yet to be observed. More details about the general subject of longitudinal polarization experiments and the related theoretical discussions may be found elsewhere [25].

5. Two-Component Theory of the Neutrino and Suggested Experimental Test

An outgrowth of the longitudinal polarization experiments was the introduction of a two-component theory of the neutrino. A forerunner of this theory had been given by Weyl [29]. Two updated versions were proposed, one by Landau [30], Lee and Yang [31] and Salam [32] and another by Majorana [33] and Serpe [34]. In both cases it was assumed that the neutrino and antineutrino are identical. A new quantity, helicity (H), was introduced, in which a value of +1 was assigned to the antineutrino (right-handed screw) and a value of -1 to the neutrino (left-handed screw). The two-component theory holds that that ν cannot behave as a right-handed screw, and that $\overline{\nu}$ cannot be left-handed.

The two-component theory of the neutrino is strictly valid only if its rest mass is exactly equal to zero. It was originally assumed that only the product of parity and charge conjugation operations PC is an invariant changing left-handed neutrinos into right-handed antineutrinos [29]. Later experiments with pion and muon decays [35] indicated that there is no difference in the helicities of such high-energy neutrinos ν_μ and antineutrinos $\overline{\nu}_\mu$ than in their counterparts in lower-energy nuclear decays (ν_e and $\overline{\nu}_e$) bolstered belief in the non-conservation of parity in the weak interaction.

The neutrino's longitudinal polarization in the weak interaction was also measured by studying nuclear recoil in β decays [13], whereby it is was found that the polarization was complete within experimental error. Neutrinos were found to behave as left-handed screws, while antineutrinos exhibited the opposite polarization, thereby providing a clear means of distinguishing between them, despite the fact that both are charge-less. The observation of nearly total polarization for the neutrinos is consistent with the v/c dependence observed for electrons, since both ν and $\overline{\nu}$ are expected to have nearly zero inertial mass and thus move with close to speed c. For Fermi transitions (ΔJ=0) the correlation distribution was found to be $1 + a\,(v/c)\cos\theta$, where v is the electron velocity and θ the angle between the electron and neutrino momentum vectors. The value of a was found to be +0.97 +/- 0.14, in agreement with the theoretical value of +1, which was predicted based on the opposite signs of the longitudinal polarization of electrons and antineutrinos. A similar cos θ dependence was noted in experiments with polarized ^{60}Co [2], where the angle is between nuclear spin and the electron velocity. For Gamov-Teller transitions (ΔJ=1), a value of a = -0.39+/- 0.05 was measured, also within experimental error of the corresponding theoretical value of a =-1/3.

Nowhere is the contrast greater between the present dynamical interpretation of the longitudinal polarization phenomenon and the two-component theory discussed above [29,30,31,32,33,34]. The latter holds that there is no such thing as a right-handed neutrino, of whatever flavor, nor is there a left-handed anti-neutrino. The dynamical model indicates, on the contrary, that it is just a matter of the conditions under which neutrinos can be observed experimentally. There is thus a need for a means of distinguishing between these two views. In the following, an experiment will be outlined which at least has the potential of settling this issue in a definitive manner, and also the broader issue of whether parity is always conserved or not.

When a spinning object collides with a wall, it normally rebounds in the opposite direction and either stops spinning or continues rotating in the same direction as before. Therefore, when a neutrino experiences a head-on collision with a heavier particle, a similar result can be expected, but this means that a left-handed neutrino *would often be converted into a right-handed one*. Yet, the two-component theory of the neutrino holds that this result is absolutely impossible, whereas the dynamical model under discussion suggests not only that it *can* happen, but even that it is a far more probable result than that the neutrino would reverse its spin as well as its velocity direction as a result of the collision.

To investigate the two-component theory, it is necessary to measure the change in spin that occurs when neutrinos collide with nuclei. If the colliding neutrino does reverse its spin direction, one unit of angular momentum must be transferred to the collision partner. Therefore, if the recoiling nucleus is in a J=0 spin state, then its total spin would change in a head-on collision as well. Observation of an accelerated nucleus in its original spin-less state would then be an indication that the backward scattered neutrino also has the same spin as it had before the collision and, therefore, that it must have changed its helicity. Such behaviour would clearly stand in contradiction to the two-component theory of the neutrino, and therefore demonstrate that the longitudinal polarization experiments are by no means incompatible with parity conservation.

Because of the known extreme penetrability of neutrinos, it is of course very unlikely that the aforementioned collision with a nucleus could be detected in practice. The possibility needs to be put in context with the original argument of Lee and Yang [3]. Under the experimental conditions of the Gamov-Teller ΔJ=1 test carried out by Wu et al. [2], the spin of the emitted electron points in the direction of the magnetic field. Therefore, they argued that if parity is conserved in this process, it should be equi-probable to detect the decay electrons in the forward as in the backward direction relative to the field vector. The experiments showed, however, that there was a large asymmetry, with more electrons emitted in the direction opposite to the field vector than along it. The amount of longitudinal polarization was found to be proportional to the velocity ratio v/c of the decaying electrons [2]. Since spin is an axial vector, while momentum is a polar vector, Lee and Yang [3] argued that parity cannot be conserved in this process, because simply inverting the coordinate system does not lead to an equi-probable experimental arrangement. i.e. with the electrons departing mainly in the forward direction relative to the magnetic field.

In their book [36,37], Frauenfelder and Henley argue forcefully in favor of parity non-conservation based on the Wu et al. [2] experiment. In their Fig. 9.6 [37] on p. 208, they show a concise illustration of the Gamov-Teller ΔJ=1 decay. The cerium magnesium nitrate nucleus with spin J=5 is subjected to a strong magnetic field **B** which is parallel to the nuclear spin. They point out that as a result at the outset the emitted electrons have almost exclusively α spin. The normalized counting rate in the forward direction is found to be only 78% of its value at a later time when the adiabatic magnetization has ceased to have an influence on the results and the spins of the electrons are just as likely to be β as α. The corresponding proportion in the backward direction is 120% of the latter value, whereby ideally the two percentages must add up to 200%. In terms of the electron counting notation used in Sect. II, $d\lambda_+ = 0.79$ and $d\lambda_- = 1.21$, so that the ratio $P = (d\lambda_+ - d\lambda_-)/(d\lambda_+ + d\lambda_-) = -0.42/2.0 = -0.21$. The latter value of P is thus seen to be consistent with v= 0.21 c as the average speed of the electrons considered in the experiment.

According to the present interpretation, these results lead to the conclusion that the probability that the *electroweak* field gradient is *positive*, i.e. in the same direction as both the electroweak field itself and also the applied magnetic field, is 0.605. The corresponding value for a neutrino would be 1.0. Since the electron spin is α at this stage of the experiment, its magnetic moment points in the opposite direction to the magnetic field, which, by virtue of the electroweak analogue of the Stern-Gerlach effect, causes a force to be applied in the *backward* direction. By elimination, the corresponding probability value for the electroweak field gradient to be *negative* is only 0.395, i.e. in the direction opposite to the magnetic field, which causes a force to be applied in the *forward* direction to the field in this case. According to the present theory, there is an *inertial effect* involved in the radiative decay process which is responsible for the above disparity, whereby the greater the speed of the particle, the greater the probability that the field will be increasing at the time that it is ejected. The result is that more electrons are counted in the backward direction than in the forward. As time goes on, the likelihood that the electron spin is parallel to the nuclear spin gradually decreases as a result of adiabatic demagnetization. Eventually, it becomes just as likely for the electrons to have β spin as α, and no further polarization is observed.

When the field direction is reversed, the counting rate bias shifts in direction, but it is again more likely that the electrons are emitted in the backward direction to the field, and by the same margin as before. On this basis, they conclude, in agreement with the earlier position of Yang and Lee [3], that parity is not conserved in this case.

Once one accepts the fact that there is an electroweak field generated in nuclear decay, however, the situation looks quite different. Everything falls into place by assuming that the **EB** field points in the direction of the nuclear spin and that the field gradient also points in this direction *at the onset* of the decay process. The Stern-Gerlach analogue therefore predicts that the direction of the force on the emitted electron is the same as for its magnetic moment, which points in the opposite direction as its spin. Thus, the favored direction of the electron momentum is opposite to that of its spin, as observed. As time goes on, the likelihood that the electron spin is in the same direction as the nuclear spin gradually decreases as a result of adiabatic demagnetization. Eventually, it becomes just as likely for the electrons to have β spin as α, and no further polarization is observed.

Finally, when the direction of the magnetic field **B** is changed, the nuclear spin also changes under the low-temperature conditions of the experiment. Consistency therefore requires that the direction of the electroweak field **EB** and its gradient at the outset of the decay process *continue to lie parallel* to the nuclear spin; thus, they are also changed relative to the original arrangement. Note that the magnetic field is completely independent of **EB**. The radiative decay takes place spontaneously even for un-oriented nuclei [11,12], for example.

The role of the magnetic field in the Wu et al. experiment [2] is to insure that the ejected electrons have α spin because of the ΔJ=1 selection rule. The calculations [2,3] indicate that prior to decay there is an even chance that the electrons will have β spin and thus that there must be a “spin-flip” in order to induce the transition. The results of the electron counting experiments [2,37] can be explained by assuming that *the spin-flip produces an electroweak field in the same direction as the applied magnetic field.* To be specific, if the magnetic field is in the north (N) direction, the electroweak field [**EB** (e^-)] must also lie in this direction. The magnetic moment of the electron lies in the south (S) direction because of its α spin. At the early stages of the transition the **EB** field is increasing, i.e. $\partial EB_z/\partial z>0$. As a result, the Stern-Gerlach force is pointed in the S direction as well, and therefore in the opposite direction to the electron spin, thereby producing the negative helicity which is observed. This state of affairs is more likely to occur when the speed of the ejected electrons is quite high, which is the cause of the observed v/c dependence of the disparity in the electron counting results [2,37].

When the direction of the **B** field is reversed so that it now points in the S direction, its parity is unchanged because it is an axial vector, as pointed out by Lee and Yang [3]. The **EB** field gradient does change sign, however, because it is a polar vector quantity. The **EB**(e^-) field is now increasing in the S direction in the early stages of the decay process, and therefore the parity of the field gradient, unlike that of the **EB**(e^-) field itself does change; the field is now increasing in the S direction, contrary to the original situation. The electrons still possess predominantly α spin because of the magnetic field, but now the spin is directed to the south (S). Therefore, the magnetic moment of the electrons has changed direction as well, and is now pointed toward the north (N). According to the electroweak Stern-Gerlach effect, this means that the force applied to the electrons is now pointed in the N direction as well, which is opposite to the direction of the electron spins (S). Again, the result is that there is a counting disparity in favor of the backward direction to the nuclear spin, as observed [2,37]. Clearly, one obtains the same conformation by leaving the magnetic field unchanged and simply inverting the coordinate system. There is no change of any physical consequence; in particular, the electron still prefers to move in the backward direction to the magnetic field.

Thus parity is conserved in the interaction when the interpretation is based on a dynamical effect which occurs when it is assumed that the electron and antineutrino already exist in the neutron prior to decay. Consistent with the experiment suggested above, one would therefore expect that the recoiled neutrinos would indeed have the same spin relative to their initial value even though their momentum is now opposite. In other words, one expects that both spin components are available to the neutrino on this basis, in opposition to the belief in the two-component theory. More discussion on this point can be found in Sect. III of Ref. [25].

6. Conclusions

The key assumption on which the two-component theory of the neutrino is based is the belief that the electron and neutrino are not present in the neutron or other nuclei prior to decay. It thereupon becomes essential to conclude from the longitudinal polarization experiments that parity is not conserved in the weak interaction. There is another way to explain the experimental results without eliminating a long-cherished law of physics, however. It is to take account of the discovery of the electroweak interaction, that is, the finding that the weak and electromagnetic interactions are simply two sides of the same coin.

One can imagine, for example, that something akin to a magnetic field is generated when an electroweak decay occurs. The effect of the electroweak field (**BE**) would be to cause decay particles to be emitted from the nucleus. One can plausibly expect that the field is inhomogeneous and therefore that it is subject to the analogue of the Stern-Gerlach effect which is well known in the study of magnetic interactions in atoms and molecules. Its effect would be greatest on the lighter particles and the elapsed time prior to its application would also be expected to be shorter for them than for heavier counterparts. As a consequence, the field **BE** would necessarily still be growing at the time that it interacts with a very light particle such as the neutrino. The field gradient $\partial BE_z/\partial z$. (see Sect. IV) would be *positive at the time of interaction*, which means that the force $F_z = \mu_z \, \partial BE_z/\partial z$ applied would have the same direction as the particle's magnetic moment component μ_z. If the latter is positive, as is assumed for the antineutrino, the latter's spin would lie in the same direction as its momentum, and it would therefore behave as a right-handed screw (positive helicity H). A neutrino, on the other hand, would behave as a left-handed screw since the direction of its spin is opposite to that of its magnetic moment. The possibility of neutrinos having magnetic moments despite their extreme penetrability has been discussed in Sect. III and in greater detail in Sect. 3 of Ref. [15].

Since the electron is a heavier particle than the antineutrino, its reaction time to the field would be expected to be longer. That means that there is now a non-zero probability that the sign of the electroweak field gradient $\partial BE_z/\partial z$ is negative at the time of the interaction and not only positive as in the case of the neutrinos. This expectation is in line with the measurements which show that the polarization of the electron in nuclear decays is not total, but that its magnitude is directly related to its v/c ratio. The electron helicity would therefore be predominantly negative, in agreement with experiment. The positron by contrast would be expected to have a predominantly positive helicity value, also as found experimentally in nuclear decays. The helicities of heavier particles such as the proton and muon can be understood to simply occur in reaction to the motion of the lighter particles in the decays, consistent with the conservation laws of energy, momentum and angular momentum. In conclusion, the above *dynamical* interpretation of the longitudinal polarization experiments has the distinct advantage of not standing in contradiction to the law of parity conservation.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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