On the discovery of symmetry violations and their effect on the trajectory of elementary particle physics research

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an erasmus essay

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October 3, 2013

Abstract

Symmetries and conservation laws have both played a vital part in the development of the Standard Model in the 20^{th} century, and discoveries of symmetry violations have helped to propel elementary particle physics forward to the theory we have today.

In this essay I attempt to introduce both the historical and theoretical background to this most important concept in particle physics, as well as give some hints about where relevant discoveries will lead us in the future.

Introduction

Since serious study of the physical world began, physicists have held certain principles to be of great operational importance. One such principle is that of symmetries and their corresponding conservation laws. It is by using such laws that many physical problems are vastly simplified, apparently disparate quantities are related, and reasonable predictions about the future – and even forthcoming discoveries – can be made.

In the early 20th century, a particular natural symmetry began to interest physicists. A century earlier, in 1815, Jean-Baptiste Biot had discovered that some molecules have a certain 'handedness' – two versions of the same molecule which look like mirror images of each other – but otherwise have the same properties, earning them the moniker 'optical isomers'. During the formulation of quantum mechanics in the 1920s, this left-right mirror symmetry, known in physics as 'parity', was successfully incorporated by Eugene Wigner; he proved that changes in the parity of atomic energy levels was based on something fundamental: the law of conservation of parity in the electromagnetic interaction [47, p. 396].

Soon thereafter, parity invariance was confirmed in the strong interaction, too; without experimental evidence to the contrary, it was likewise assumed that the same would be true of the weak interaction. However, tentative signs that this might not be the case were noted in 1956 by two young physicists from China, Tsung Dao Lee and Chen Ning Yang, after a careful review of the literature available to them. Lee, Krishna Myneni explains, had been described as "one of the most brilliant theoretical physicists then known". Of Yang we read, "For a while Yang had tried experimental physics, but it was not to be. Other graduate students had teased him, 'Where there was a bang, there was Yang'." [29]

Experimental incompetencies aside, it was clear these physicists were sharp, and seeking to make a name for themselves. Indeed, in this respect, it might be said they overachieved: Yang & Lee published an article which in many ways changed our fundamental understanding of Physics, proposing a solution to a problem known then as the 'τ-θ puzzle'.

The τ-θ Puzzle

When observing the decays of cosmic particles, two University of Manchester physicists, G. D. Rochester and C. C. Butler, noted decays in the shape of a V, where two oppositely charged particles came from nowhere in the bubble chamber. After more research, this particle was confirmed and dubbed the τ, with decay $\tau \rightarrow 2\pi$.[1] Later, it was discovered that another particle decayed into three pions, and this was named the θ particle. However, surrounding these particles was a tantalizing mystery. When their properties were measured, they both had the same spin, mass, etc., but the decay products appeared to have opposite parities: the τ had positive and the θ had negative parity.

Naturally, from the similarity of their properties, it seemed unlikely these were two distinct particles, but given that parity was assumed to be conserved, this conclusion found itself excluded. Noting, however, this assumption had never actually been experimentally tested, Lee and Yang proposed [24] several experiments to rectify this, and simultaneously found a solution for this puzzle.

The first experiment they proposed was based on the $\beta-$decay in radioactive ^{60}Co nuclei, whose decay is as follows:

$$^{60}\text{Co} \rightarrow^{60} \text{Ni}^* + e^- + \bar{\nu}_e \tag{1}$$

Assuming parity *is* violated in this interaction, the electrons ought to be ejected differently before and after the parity transformation.

The experiment was soon undertaken by C. S. Wu and other collaborators in the year 1957. [8] In her experiment, Wu aligned the spins of a sample of ^{60}Co with an external magnetic field. The sample was cooled to 0.01K to ensure as many nuclear spins would align as possible. Wu then counted the resulting decay products of the atoms along with the direction of their propagation. After a parity transformation was applied, by means of flipping the magnetic field direction, the same measurements were taken once again. A schematic representation of the experiment is given in Figure 1.

The results of the experiment were surprising and ground-breaking (figure 2). Rather than the electrons being emitted in the same relative direction before and after the parity transformation, it was observed the electrons

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[1] This is not the τ meson discovered later, but the name at the time for the particle which later came to be identified, along with the θ, as the kaon.

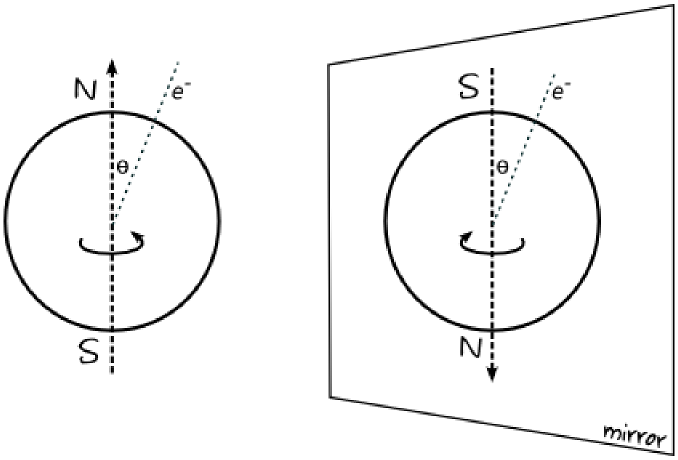

Figure 1: Schematic representation of the experiment performed by Wu et al.[a] *On the left, the electrons can be seen being emitted in the direction of the nuclear spin, whilst on the right they are emitted opposite to the nuclear spin - that is, mirror symmetry is broken in the beta decay of* ^{60}Co.

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[a] A far more beautiful artistic schematic exists which unfortunately cannot be reproduced [44].

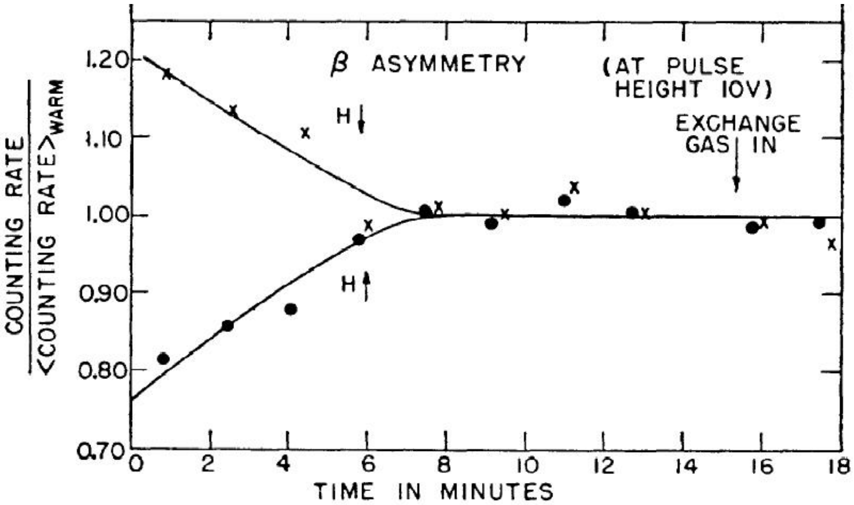

Figure 2: The results of the experiment from Wu's original publication. As can be seen, the β *particles are emitted in a preferred direction with respect to the spin, contrary to that predicted by Lee and Yang if parity were conserved. The strength of the asymmetry fades as time passes, since the sample heats up causing the orientation of the nuclear spins to become less orderly.*

"preferred" a certain direction, as denoted by the upward-facing arrow labelled "e^-" of Figure 1. And this effect was not small: the asymmetry was pronounced.

Alongside Wu's experiment, a further test of $\hat{P}$-invariance suggested by Lee and Yang in their original paper was in the decay:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{2}$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{3}$$

Parity conservation can be tested in this decay chain because, as Garwin et al report, if the symmetry is broken, there should be an asymmetry in the polarization of the muons along the direction of motion; this can be determined by the distribution of electrons from the decay of the muons. [13] The experimentalists were initially sceptical any sizeable effect would be observable, but after hearing of the magnitude of the asymmetry discovered by Wu, and liaising with her privately [25], they undertook the experiment in February 1957, publishing the results directly after Wu's in the same journal. [13] An angular distribution of the electrons following that predicted by Lee and Yang [24][2] was indeed observed, confirming parity is not conserved in the weak interaction.

Effects on the Standard Model

The effect of the discovery of parity nonconsevation on elementary particle physics research is hard to understate; it is as though, as one author put it, a 'sacred principle' governing the known Universe had been overturned [39, p. 261], and many physicists were not comfortable with the idea [22]. The discovery was deemed so important that the Nobel Committee forsook their usual tardiness, rewarding Lee and Yang the same year the experimental confirmations were published. [30]

Proof of parity violation, however, wasn't and end in itself. In fact, this discovery opened up a conscious search for more fundamental symmetries, such as the combined operation CP discussed below.[3] Likewise, a search for

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[2] Lee & Yang predicted a distribution $1 + \alpha \cos\theta$, where θ is measured from the velocity vector of the incident muons. Garwin et al found $\alpha = -1/3 \pm 10\%$. [13] If parity violation were not present, we should expect α to be precisely zero. [24]

[3] $\hat{C}$ is charge-conjugation symmetry – swapping particles for antiparticles.

a mathematical explanation for parity violation, *i.e.* the mechanism which allows for it in the weak interaction, began, resulting in what is often referred to as its *chiral nature*.

The Chiral Nature of the Standard Model Two concepts integral to elementary particle physics are 'helicity' and 'chirality'. When we speak of the helicity of a particle, we are speaking of the apparent handedness of the particle, given by the projection of its spin onto its momentum vector (see figure 3). When we speak of chirality, we are speaking of an innate property of the particle, its 'intrinsic' handedness. Chirality is not necessarily directly observable (see below) but it is the term which appears in the mathematics of electroweak theory.

To illustrate the difference between the two concepts, picture a spacecraft following a moving particle with right-handed helicity and chirality through space. As long as the spacecraft is slower than the particle, the particle looks right-handed. But if the ship speeds past the particle, its helicity now appears to have been reversed, since relative to the spaceship, the particle is now travelling in the opposite direction and its momentum vector has changed sign; its chirality, an intrinsic property, would nevertheless remain invariant.

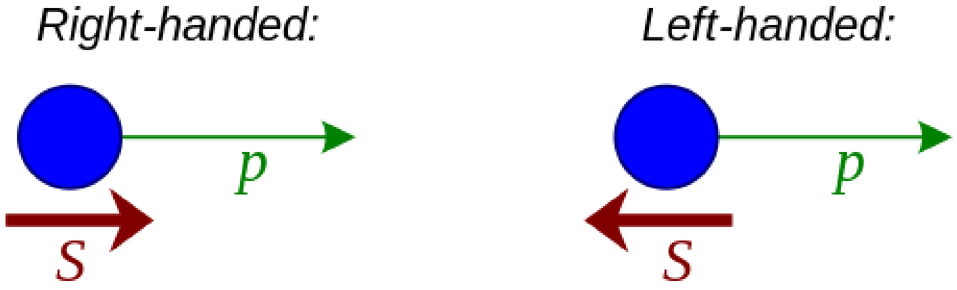

Figure 3: Particle helicity. When aligning your right-hand's thumb with $\vec{p}$, if your fingers trace the spin of the particle, the particle is right-handed, otherwise it is left-handed. Diagram from Wikipedia [20].

The concept of chirality in the Standard Model has some interesting corollaries. These are present in various experiments which demonstrate two important facts: (a) the weak interaction only couples to left-handed chirality particles (right-handed antiparticles); and (b) right-handed neutrinos (left-handed antineutrinos) do not exist in nature.[4] This point was demonstrated by Goldhaber in his famous and rather ingenious experiment [15].

Incorporating these observations into the Standard Model began with searching for a new mathematical structure for the Fermi theory of Beta decay, proposed by Enrico Fermi 1933 based on analogy to QED [11]. Fortunately, the theory proved very adaptable to new discoveries [12]. The conclusion derived by Marshak & Sudarshan [41] was that the weak interaction exhibited '**V-A** structure', that is vector minus axial vector coupling.[5] They showed that neither V-V nor A-A couplings allow for any parity violation; V-A coupling allows for *maximal* parity violation.[6]

These effects of chirality are manifest, for instance, in the branching ratios of pion decays into the electron and muon channels:

$$\pi \to e\ \nu_e \tag{4}$$

$$\pi \to \mu\ \nu_\mu \tag{5}$$

One would naïvely expect the electron mode to be preferred since it has a larger phase space – about $3^1/_2$ times as large as the muon [5, p. 5] – but due to helicity considerations, the opposite is observed [1]:

$$\frac{\mathrm{BR}(\pi \to e\nu)}{\mathrm{BR}(\pi \to \mu\nu)} = (1.230 \pm 0.004) \times 10^{-4} \tag{6}$$

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[4] Or at least have not yet been observed and are not described by the (current) Standard Model: if they do exist, which is conceivable, since neutrino oscillations require they have non-zero mass, they could prove to be an interesting candidate for dark matter as discussed below. A review of right-handed neutrino theory is given in [6].

[5] When you write down fermion currents of the weak interaction, you find terms of the form

$$j^\mu \propto \bar{u}_3 \underbrace{(\gamma^\mu - \gamma^\mu\gamma^5)}_{\mathbf{V-A}} u_1$$

where the *u*s are particle spinors (spinors explained in [28]). This is necessarily parity-violating since vectors and axial vectors transform differently under $\hat{P}$, namely $\hat{P}\mathbf{V}(\vec{x}) = -\mathbf{V}(\vec{x})$ whilst $\hat{P}\mathbf{A}(\vec{x}) = \mathbf{A}(\vec{x})$ [42, p. 164]. Due to the equal **V** and **A** contributions, this results in maximal parity violation in the fermion current (see footnote 6).

[6] Maximally violating means that when $\hat{P}$ is applied, the resultant particle is *never* observed, i.e. $\hat{P}|\nu_L\rangle = |\nu_R\rangle$ which is not observed, and so on for other combinations. As discussed, this may transpire not to be a perfectly accurate description of nature, see footnote 4.

The pion has spin $S = 0$, and so the resultant spins of the ν and e/μ, both spin half, must sum to zero. If we focus on π^+ decay, taking on board (b), *i.e.* that only left-handed neutrinos are observed, we can place a constraint on the e^+/μ^+ that they likewise be left-handed.[7] *But from (a) the weak interaction only couples to right-handed antiparticles!*

We can see now why the electron decay mode must be suppressed: although the e^+/μ^+s must be ejected with left-handed helicity, there can be a contribution to that helicity state from *right-handed chiral* states, and, importantly, this contribution goes with mass. We can think of it in a more concrete way in that the higher the mass of a particle, the lower its velocity will be after being emitted. Therefore, the degree of polarization, which is velocity dependent, will also be lower – in other words, a higher proportion of the particles will having non-matching helicity and chirality.[8] For this reason, the muon is more likely to couple to the weak interaction than is the positron in this decay, and the electron decay mode is dramatically suppressed.

Symmetry Restored: CP It is because of the discrepancy between left and right that Russian physicist Lev Landau sought to find a more fundamental symmetry obeyed by nature of which P (and C) were perhaps only manifestations. In 1957 he proposed that, although C and P may be independently violated, perhaps the combined operation CP will always be conserved in nature [22]. He was building upon theoretical progress [32] made by Murray Gell-mann and Abraham Pais [14] who in 1955[9] had introduced new particles consisting of superpositions of neutral particles, for example the neutral kaon and antikaon, in order to construct particles of positive and negative C-parity:[10]

$$K_1 = (K^0 + \bar{K}^0)/\sqrt{2} \tag{7}$$
$$K_2 = (K^0 - \bar{K}^0)/\sqrt{2} \tag{8}$$

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[7] **V-A** structure conserves helicity.

[8] The degree of polarization is velocity-dependent: $P \equiv \frac{N_R - N_L}{N_R + N_L} = \pm v/c$ for RH/LH. The fraction with the right/wrong helicity is $\frac{1}{2}(1+P) = \frac{1}{2} \pm \frac{1}{2}\frac{v}{c}$. For approximately massless neutrinos $m_\nu \approx 0$, we find $v_\nu \approx c$, therefore the fraction of neutrinos with "wrong" helicity is approximately 0 (c.f. point (b)).

[9] Note that this is *before* Lee and Yang proposed the nonconservation of $\hat{P}$ (and $\hat{C}$).

[10] *I.e.* $\hat{C}|K_1\rangle = +|K_1\rangle$; $\hat{C}|K_2\rangle = -|K_2\rangle$.

That these particles should exist seems strange at first sight, and it was originally received with scepticism that two different particles could superpose in such a manner [1]. Fortunately, the correctness of the superposition is experimentally testable: according to a prediction first made by A. Pais & O. Piccioni [34], the mass eigenstates $|K^0\rangle$, $|\bar{K}^0\rangle$ should, by means of a second order weak interaction,[11] "mix" or oscillate during propagation. So whilst a beam may begin as a pure beam of K^0, at some point later in the propagation, there should be a mixture of K^0 and $\bar{K}^0$ present in the beam. The presence of antikaons will be detectable by their different decay modes.

Presuming Landau was correct about combined CP invariance, these particles must decay as $K_1 \to 2\pi$ and $K_2 \to 3\pi$ since

$$CP(K_1) = CP(2\pi) = +1 \tag{9}$$

$$CP(K_2) = CP(3\pi) = -1 \tag{10}$$

The particles must also have different lifetimes, since lifetimes are inversely proportional to the phase space volume available, which is necessarily different for both decays, since the K_1 is decaying into one fewer particle of roughly equal mass. Often these particles are therefore assigned the more descriptive labels K_S to the short-lived K_1, and K_L to the long-lived K_2 respectively.

This particle mixing was confirmed by experiments which allowed kaons, themselves a superposition, $|K^0\rangle = \frac{1}{\sqrt{2}}(|K_S\rangle + |K_L\rangle)$[12], to propagate long enough that all short-lived particles decayed and the beam consisted of purely K_L particles. When the beam was shot through a target, the $K^0/\bar{K}^0$ behaved radically differently in the medium, since the $\bar{K}^0$s have many more decay channels open to them in the matter target and are thus almost completely absorbed [3, p. 198]. This meant that the beam was no longer purely K_L (50/50 kaon/antikaon), but rather a new superposition consisting of both K_L and K_S particles once more, a phenomenon known as coherent regeneration. Since these predictions were made assuming CP invariance, all indications were that Landau was correct.

However, when trying to replicate this experiment in 1964, Cronin & Fitch *et al* [10] observed the decay $K_2 \to 2\pi$, supposedly forbidden by CP invariance. This observation was the first discovery of CP violation, and

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[11] The change in strangeness $\Delta S = 2$: a first order interaction changes strangeness by a unit at the most.

[12] Obtained from (7) & (8).

won them a Nobel Prize in 1980 [31]. The discovery shows CP to be only an approximate symmetry of the $K^0 - \bar{K}^0$ system and, as a result, we can no longer identify K_S precisely with the K_1, but rather must write (without normalization)

$$|K_S\rangle = |K_1\rangle + \bar{\varepsilon}|K_2\rangle$$

$$|K_L\rangle = |K_2\rangle + \bar{\varepsilon}|K_1\rangle$$

where $\bar{\varepsilon}$ is a small quantity. CP violation has since been observed in the decays of several other particles, including those with charm and beauty[13] at LHCb and elsewhere. [2]

It is noteworthy that there are no generally accepted violations of the combined symmetry CPT, where T is time-reversal symmetry. [46] As such, this symmetry is considered universally valid, which is required by the Standard Model, derived in [26].

Effects on current and future research

CP Violation and Baryogenesis Why the Universe is matter-dominated and not charge-symmetric has long been a vexing mystery whose solution seems so elusive. Andrei Sakharov, a Russian nuclear physicist inspired by the just-discussed CP violation in the kaon sector, demonstrated [38] three conditions which must have been present at the beginning of the Universe in order for the current matter-antimatter asymmetry to exist; one of these was a CP violating process or processes.

Therefore, that CP symmetry is not always and everywhere invariant opens up the possibility that we can finally solve this challenging mystery. It has been calculated by some, for example Farrar & Shaposhnikov [27], that the Standard Model *can* account for the observed baryon asymmetry. However, others disagree this is possible, claiming we must rely on physics beyond the Standard Model to solve this problem. This has led to the building of many detectors, perhaps most notably LHCb which has been specifically designed to be sensitive to any effects from unknown physics, and to probe the edge of CP violation in the Standard Model (see [4]).

Precise Confirmation of the Higgs The Higgs particle is so famous that talking about it in an essay on particle physics feels in many ways clichéd, but

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[13] *i.e.* containing charm or bottom quarks.

no essay on symmetries could possibly be complete without at least a cursory mention. The particle, whose discovery at the LHC was confirmed in March 2013 [33], is a quantum excitation of the 'Higgs field', a scalar field which pervades the Universe and interacts with certain particles to give them mass. The Higgs field was introduced by a number of authors [7][19][17] in order to solve the "mass problem" – the problem of how some particles acquire mass whilst the symmetries understood to be governing the reactions do not allow it.[14]

The way the Higgs mechanism solves this problem is to posit that gauge bosons do not have mass at high energies (*i.e.* high temperatures) where the symmetry is unbroken, but that at a certain energy level, the potential term in the electroweak Lagrangian becomes perturbed, producing a new lowest energy level called the "vacuum expectation value" (vev). When vacuum states fall to the vev, the symmetry around the centre of the potential is bro-

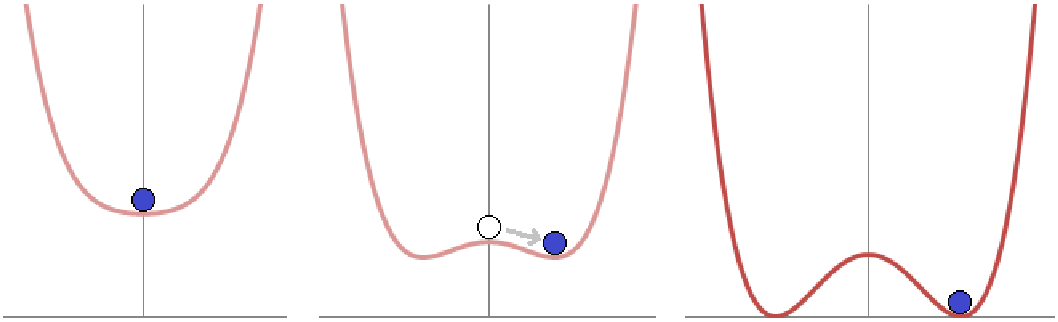

Figure 4: 2D diagram of the electroweak potential at different energies. On the left we see the electroweak potential at high energies without any breaking of symmetry. In the middle, the energy is falling, and the potential takes the form of a "mexican-hat". A system at the centre of the potential must spontaneously choose which way to fall. On the right, the system has fallen to a state of lowest energy, the vev, thus breaking the symmetry at the centre of the potential. Goldstone showed this process requires the existence of a massless boson [16]. Electroweak symmetry is thrice broken, producing three massless bosons: relating these to the (massive) gauge bosons (i.e. $W^{\pm}, Z$) is the essence of the Higgs mechanism. A fourth degree of freedom becomes the Higgs particle.[a] Diagram courtesy of FT2. [45]

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[14] The introduction of mass terms for the electroweak gauge bosons (*i.e.* $W^{\pm}, Z$) without invoking the Higgs mechanism poses problems because it leads to infinite interaction cross sections and breaks renormalizability.

[a] The gauge group of electroweak theory is SU(2)×U(1), which has four generators.

ken (see figure 4). This process is known as *electro-weak symmetry breaking*, and results in massive gauge bosons and the Higgs particle. It is similar to what we observe in a bar magnet. When the iron is hot we see the orientation of atomic magnetic moments is disorderly and random, giving no overall magnetization. But as it cools to below the Curie temperature, their orientations spontaneously "freeze out" giving the iron bar as a whole a definite magnetic field in a certain direction, though there is nothing "pushing" the field to choose that orientation [40]. In the same way, as the energy scale drops in the electroweak interaction, the symmetry is spontaneously broken and the massive gauge bosons "freeze out", as does the Higgs particle.

But the discovery of the Higgs particle alone is not enough, since there are extensions to the minimal Standard Model such as "two Higgs-doublet models", "Unparticle physics", variants of Supersymmetry, and others, which often incorporate more than one Higgs field – and by extension more than one Higgs boson – and which can only be distinguished from the Standard Model by analyzing the precise decay modes and branching ratios of the LHC Higgs particles. Therefore, critical to discovering whether our understanding of electroweak symmetry-breaking is correct is the precise analysis of the properties of the Higgs boson. This will take many more years of data gathering and processing after the upgrade to the LHC is completed in 2015.

Strong CP Violation and Dark Matter There are many candidates for the make-up of dark matter. Particle physicists have been called in by Cosmologists to help solve the problem by developing theories for new – that is, non-Standard Model – particles of which it could consist. One suggestion given is the axion. Axions are weakly interacting elementary particles generated by the Peccei-Quinn mechanism [35]. Somewhat similarly to the Higgs mechanism, this involves the spontaneous breaking of a new symmetry, generating the axion particle.

Axions are postulated to be incredibly light in mass, of the order μeV-meV, and at least one experiment has claimed [9] positive results in its search (athough [21] initially contested these results). It is also possible dark matter consists of other non-Standard Model particles, such as right-handed neutrinos, forbidden by Standard Model chirality as discussed above. Alternatively, primordial black holes may render the entire search for an explanation based in strong or weak CP violation unfruitful [37, p. 175].

The Peccei-Quinn mechanism may be even more powerful, since it also provides an explanation for the stark suppression of CP violation in the strong interaction, known as the *strong CP problem*. Without this mechanism, this suppression would seem to point to a very high degree of fine-tuning.

Grand Unified Theories In this essay we have discussed the symmetries of the Standard Model at length, and considered the unification of the electromagnetic and weak interactions into the electroweak interaction. The question now stands, Is there a more fundamental symmetry which can unify this with the strong interaction? This is the aim of Grand Unified Theories (GUTs). GUTs are an area of research building directly upon the observations of symmetry breaks and violations in nature. Unfortunately, they tend to be rather more complicated than the current Standard Model, such as by introducing new dimensions of space, and the particles they predict are commonly of energies $\sim 10^{14}$ GeV, vastly higher than the LHC can produce, $\sim 10^{4}$ GeV, making them almost a purely mathematical pursuit.

A Theory of Everything Rather grandiose-sounding and not without warrant, a Theory of Everything would unify a GUT with the gravitational interaction. Some consider this the goal of all physical research. Others, notably including Stephen Hawking, consider it an unlikely possibility [18]. But it seems it will be a long way into the future before the existence of a Theory of Everything will even be testable.

Final Thoughts

Physics has come a long way from the early days of the formulation of quantum mechanics. We have built up a knowledge of the world, and seen those pillars of understanding crumble time and again. However, emotional attachments to our prized theories notwithstanding, this is not disheartening, for the quest for true knowledge and understanding about the world is immeasurably more important than retaining an inaccurate theory, no matter how well it has performed in the past, or how much we want it to be true. This has been the case with many of the fundamental tenets of physics relating to symmetries, eviscerated in the last century by the discoveries discussed. We must always bear this in mind as we discover new paths into the future of science, for who knows which will be the next pillar to fall?

References

[1] Measurement of the pion branching ratio at TRIUMF. In *19th Particle and Nucei International Conference*, pages 564–566. American Institute of Physics, Jul 2011.

[2] M. Altarelli. CP violation in charm and beauty decays at LHCb. Jan 2013 **arXiv**:1301.3082.

[3] Robert N. Cahn and Gerson Goldhaber. *The Experimental Foundations of Particle Physics*. Cambridge Unviersity Press.

[4] LHCb Collaboration. Roadmap for selected key measurements of LHCb. *LHCb-PUB-2009-029*, 1999 **arXiv**:0912.4179.

[5] Milind Diwan. Decay rates: Pions, April 2007. `http://www.phy.bnl.gov/~diwan/talks/mine/Intensity-Frontier-Colloquium/part4.ppt`. *Retrieved 15 Aug 2013*.

[6] Marco Drewes. The phenomenology of right handed neutrinos. *Int. J. Mod. Phys. E.*, 22:1330019, 2013 **doi**:10.1142/S0218301313300191. **arXiv**:1303.6912.

[7] F. Englert and R. Brout. Broken Symmetry and the Mass of Gauge Vector Mesons. *Phys. Rev. Lett.*, 13(9):321–323, Aug 1964 **doi**:10.1103/PhysRevLett.13.321.

[8] C. S. Wu et al. Experimental test of parity conservation in beta decay. *Phys. Rev.*, 105(4):1413–1415, Feb 1957 **doi**:10.1103/PhysRev.105.1413.

[9] E. Zavattini et al. Experimental observation of optical rotation generated in vacuum by a magnetic field. *Phys. Rev. Lett.*, 96(11):110406, Mar 2006 **doi**:10.1103/PhysRevLett.96.110406.

[10] J. W. Cronin et al. Evidence for the 2π Decay of the K_2^0 Meson. *Phys. Rev. Lett.*, 13(4):138–140, Jul 1964 **doi**:10.1103/PhysRevLett.13.138.

[11] Enrico Fermi. Tentativo di una teoria dei raggi β. *Il Nuovo Cimento*, 11(1):1–19, 1934 **doi**:10.1007/BF02959820.

[12] Enrico Fermi Fred L. Wilson. Fermi's theory of beta decay. *American Journal of Physics*, 36(12):1150, Dec 1968 **doi**:10.1119/1.1974382.

[13] Richard L. Garwin, Leon M. Lederman, and Marcel Weinrich. Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon. *Phys. Rev.*, 105(4):1415–1417, Feb 1957 **doi**:10.1103/PhysRev.105.1415.

[14] M. Gell-Mann and A. Pais. Behavior of Neutral Particles under Charge Conjugation. *Phys. Rev.*, 97(5):1387–1389, Mar 1955 **doi**:10.1103/PhysRev.97.1387.

[15] M. Goldhaber, L. Grodzins, and A. W. Sunyar. Helicity of neutrinos. *Phys. Rev.*, 109(3):1015–1017, Feb 1958 **doi**:10.1103/PhysRev.109.1015.

[16] J. Goldstone. Field theories with superconductor solutions. *Il Nuovo Cimento*, 19(1):154–164, 1961 **doi**:10.1007/BF02812722.

[17] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble. Global Conservation Laws and Massless Particles. *Phys. Rev. Lett.*, 13(20):585–587, Nov 1964 **doi**:10.1103/PhysRevLett.13.585.

[18] Stephen Hawking. Gödel and the end of physics. 2002. `http://www.damtp.cam.ac.uk/events/strings02/dirac/hawking/`. *Retrieved 12 Aug 2013*.

[19] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13(16):508–509, Oct 1964 **doi**:10.1103/PhysRevLett.13.508.

[20] Stannered. Right left helicity.svg. Wikimedia Commons, Feb 2007. `http://en.wikipedia.org/wiki/File:Right_left_helicity.svg`.

[21] P. C. Ferreira J. T. Mendonca, J. D. de Deus. Higher Harmonics in Non-Linear Vacuum from QED Effects Without Low Mass Intermediate Particles. *Phys. Rev. Lett.*, 97(10):100403, 2006 **doi**:10.1103/PhysRevLett.97.100403. **arXiv**:hep-ph/0606099v3.

[22] L. Landau. On the conservation laws for weak interactions. *Nuclear Physics*, 3(1):127 – 131, 1957 **doi**:10.1016/0029-5582(57)90061-5.

[23] T. D. Lee, Reinhard Oehme, and C. N. Yang. Remarks on possible noninvariance under time reversal and charge conjugation. *Phys. Rev.*, 106(2):340–345, Apr 1957 **doi**:10.1103/PhysRev.106.340.

[24] T. D. Lee and C. N. Yang. Question of parity conservation in weak interactions. *Phys. Rev.*, 104(1):254–258, Oct 1956 **doi**:10.1103/PhysRev.104.254.

[25] David Lindley. Landmarks: Breaking the mirror. *Phys. Rev. Focus*, 22:19, Dec 2008 **doi**:10.1103/PhysRevFocus.22.19. *Retrieved 15 Aug 2013*.

[26] Gerhart Lüders. Proof of the TCP Theorem. *Annals of Physics*, 281:1004 – 1018, 2000 **doi**:http://dx.doi.org/10.1006/aphy.2000.6027.

[27] G. R. Farrar M. E. Shaposhnikov. Baryon asymmetry of the universe in the minimal standard model. *Phys. Rev. Lett.*, 70(17):2833–2836, 1993 **doi**:10.1103/PhysRevLett.70.2833. **arXiv**:hep-ph/9305274.

[28] Victoria Martin. The Dirac Equation and Spinors. *University of Edinburgh*, 2012. `http://www2.ph.ed.ac.uk/~vjm/Lectures/SHParticlePhysics2012_files/PPNotes2.pdf`.

[29] Krishna Myneni. Symmetry destroyed: The failure of parity. Dec 1984. `http://ccreweb.org/documents/parity/parity.html`. *Retrieved 15 Aug 2013*.

[30] Nobelprize.org. The nobel prize in physics 1957. `http://www.nobelprize.org/nobel_prizes/physics/laureates/1957/`. *Retrieved 6 Aug 2013*.

[31] Nobelprize.org. The nobel prize in physics 1980. 2013. `http://www.nobelprize.org/nobel_prizes/physics/laureates/1980/`. *Retrieved 15 Aug 2013*.

[32] L. B. Okun. On the neutron-antineutron oscillations. Jun 2013 **arXiv**:1306.5052.

[33] Cian O'Luanaigh. New results indicate that new particle is a higgs boson. *home.web.cern.ch*, 2013. `http://home.web.cern.ch/about/updates/2013/03/new-results-indicate-new-particle-higgs-boson` *Retrieved 19 Aug 2013*.

[34] A. Pais and O. Piccioni. Note on the decay and absorption of the θ^0. *Physical Review*, 100:1487–1489, Dec 1955 **doi**:10.1103/PhysRev.100.1487.

[35] R. D. Peccei and Helen R. Quinn. CP conservation in the presence of pseudoparticles. *Phys. Rev. Lett.*, 38(25):1440–1443, Jun 1977 **doi**:10.1103/PhysRevLett.38.1440.

[36] Donald H. Perkins. *Introduction to High Energy Physics*. Cambridge University Press, 4 edition, 2000.

[37] B. Ryden. *Introduction to Cosmology*. Ohio State University, Jan 2006.

[38] A.D. Sakharov. Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe. *Pisma Zh.Eksp.Teor.Fiz.*, 5:32–35, 1967 **doi**:10.1070/PU1991v034n05ABEH002497.

[39] J. J. Sakurai. *Modern Quantum Mechanics (Revised Edition)*. Addison Wesley, September 1993.

[40] William Seager. *Natural Fabrications*. Springer, 2012. `http://www.springer.com/physics/complexity/book/978-3-642-29598-0`.

[41] E. C. G. Sudarshan and R. E. Marshak. Chirality Invariance and the Universal Fermi Interaction. *Phys. Rev.*, 109(5):1860–1862, Mar 1958 **doi**:10.1103/PhysRev.109.1860.2.

[42] J. Suhonen. *From Nucleons to Nucleus: Concepts of Microscopic Nuclear Theory*. Theoretical and Mathematical Physics. Springer, London, 2007.

[43] F. Tanedo. Helicity, chirality, mass, and the higgs. *Quantum Diaries*, Jun 2011. `http://www.quantumdiaries.org/2011/06/19/helicity-chirality-mass-and-the-higgs/`. *Retrieved 15 Aug 2013*.

[44] Ele <the.minouette>. Mme. wu and the violation of parity, Oct 2011. `http://www.flickr.com/photos/22611996@N02/6219132038/in/photostream/`. *Retrieved 15 Aug 2013*.

[45] FT2 (`http://en.wikipedia.org/wiki/User:FT2`). Spontaneous symmetry breaking (explanatory diagram), Dec 2012. `http://en.wikipedia.org/wiki/File:Spontaneous_symmetry_breaking_%28explanatory_diagram%29.png`.

[46] N. Russel V. A. Kostelecky. Data tables for lorentz and cpt violation. *Reviews of Modern Physics*, 83(1):11–31, 2011 **doi**:10.1103/RevModPhys.83.11. **arXiv**:0801.0287.

[47] C. N. Yang. The law of parity conservation and other symmetry laws of physics. *Nobel Lectures Physics: 1942–1962*, 1964.