An Exploratory Report into The Applications & Theory of Discrete Symmetry

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Abstract

This follow-up report begins with an in-depth discussion of both theory and findings from the Wu and Fitch-Cronin experiments, which proved P (parity) and CP (charge-parity) violation respectively. The observable symmetry breaking on a local and universal scale are explored. The report culminates on discussion of Sakharov's baryogenesis conditions proposed for matter-antimatter asymmetry and suggests a potential theoretical explanation to this phenomenon.

1 Background & Theory for The Wu Experiment

A parity transformation in the context of physics refers to the reversing of the signum of all spatial coordinates at once:

$$\vec{P} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} \tag{1}$$

In 1927, Eugene Wigner [1] postulated the principle of parity conservation, in which the current world and a mirror version would behave the same; except that signum of coordinate reverses polarity. Experiments in following years proved that parity was conserved in electromagnetic and strong interactions. However, the accepted principle could not explain the decay of two types of kaons, which was known as the $\tau - \theta$ puzzle. Later theorists would approach Dr Wu, who would eventually conduct the experiment that proved parity violation in the weak interaction and resolve the$\tau - \theta$ puzzle.

The experiment was conducted in 1956, with the main purpose to establish if weak interactions were parity symmetric as with electromagnetic and strong interactions. If P was conserved, then the current world and a mirrored world would be indistinguishable. However, if the opposite were true, a mirrored world would in fact be distinguishable. At the time, Dr Wu was an expert on beta decay spectroscopy and designed an experiment which focused on the decay products of the beta decay of Cobalt-60. This was set up in a uniform magnetic field which provided a reference direction along which the nuclear spins could be aligned with [2].

Temperatures were kept close to absolute zero to avoid the thermal motion of particles disturbing their alignments. Cobalt-60 is an unstable nucleus and decays via beta-minus decay. This involves a neutron becoming a proton within the nucleus and emitting an electron as well as an anti-electron neutrino – this is done in order to conserve the lepton number for the interaction. This results in a stable but excited Nickel-60 nucleus which releases two photons to reach an un-excited state. This decay can be represented as:

$$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni} + e^{-} + \bar{v}_e + 2\gamma \tag{2}$$

The photons each decay releases are treated as a control in this experiment, as they correspond to the electromagnetic interaction, which was been previously proven to be parity symmetric [3]. This meant that the emission of photons would be isotropic and have no preference. Apart from being used as a control, it was used to align Cobalt-60 with the magnetic field and measure how well the spins were aligned using the distribution of their emission. Cobalt-60 carries spin, which is a pseudo-vector as it is not affected by a parity transformation. However, direction of the momentum of the decay products are affected as it is a polar vector. This means that there would be a disparity in the momentum of an electron and its mirror image. However, its spin would remain invariant (as shown in Figure 1) and thus violate parity conservation.

The only way it could be parity symmetric is if there is no preference in the direction of emission, as there would be an equal distribution of emissions that would appear identical in both worlds.

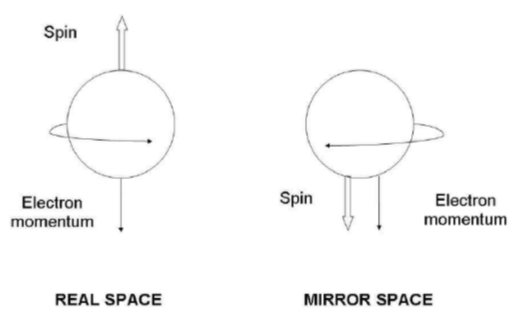

Figure 1: Visual representation of spin and beta decay in mirror space.

2 Results from The Wu Experiment and Subsequent Experiments

Now given the structure and the aim of the experiment, Dr Wu was able to demonstrate an apparent violation of parity. The results proved shocking to the Physics community and notable physicists, including Wolfgang Pauli and Richard Feynmann.

The Cobalt-60 isotope, contradictory to common belief, was found to emit electrons in a preferred direction. This causes the entire concept of parity symmetry to collapse, with regards to the weak interaction. This result clearly distinguished between right and left-handedness in Physics contrary to the assumption posited by Wigner[4]. After the Wu experiment was published, other experiments were conducted with different weak interactions including pion, and muon decay which further demonstrated a violation of parity[5]. This would, in essence, give a universal direction in which any frame can be based upon, the left-hand could be distinguished from the right hand through the weak interaction[6].

One of the consequences of these results would be the differentiation between matter and antimatter. This was first demonstrated using Cobalt isotope Co^{58}, which had a positive beta decay that emitted positrons preferably in the polar opposite direction relative to the electron emitted in the original Wu experiment [7]. Shortly after this finding, experiments were conducted on the angular momentum conservation using the same setup as the original Wu experiment. The measurements would entail that the Co-60 atom would have an angular momentum spin of +5 and the subsequently decayed Nickel atom with an angular momentum spin of +4. Thus, the electron and anti neutrino would both have a spin of $+\frac{1}{2}$ and since the electron is emitted in a preferred direction, it would be considered left-handed [8] .

This experiment paved a labyrinth of questions in the field of symmetry and changed the understanding of the basics of modern physics. After this revolutionary discovery, a domino effect of questioning of presumed physical symmetries were placed under consideration and extreme doubt. Throughout this report, more experiments will be covered regarding testing and understanding other physical symmetries. Specifically, charge conjugation symmetry was immediately questioned and violated through the decay of mesons [9].

In essence, the results of this experiment proved Lee and Yang's hypothesis and solved the $\tau - \theta$ puzzle by demonstrating P violation, although CP was assumed to be invariant [10]. In the next section, we discuss experimental evidence for CP violation in more depth, by beginning with an exploration of neutral kaon mixing.

3 The Fitch-Cronin Experiment Revisited

Trivially, a neutral particle is its own antiparticle. However, this is not so for neutral kaons since they have strangeness. This results in the neutral kaon K^0

(of strangeness +1) having an antiparticle $\bar{K^0}$ of opposite strangeness. Due to this definite strangeness, $|\bar{K^0}\rangle$ and $|K^0\rangle$ are referred to as strange or *weak eigenstates* [11]. Neutral Kaons oscillate between these states via the mechanism shown in Figure 2.

Mass eigenstates can be described as free particle solutions to the wave equation [12]. Here, K-short and K-long mass eigenstates ($|K^0_s\rangle$ and $|K^0_L\rangle$) are obtained when wave functions for $|\bar{K^0}\rangle$ and $|K^0\rangle$ are applied to Schrödinger's equation [11]. If CP were invariant (which Cronin et al. disproved), these mass eigenstates would be written as linear combinations of weak eigenstates, as follows [13] [14]:

$$|K^0_s\rangle \equiv |K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\bar{K^0}\rangle\right] \tag{3}$$

$$|K^0_L\rangle \equiv |K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K^0}\rangle\right] \tag{4}$$

In this case, $|K^0_s\rangle$ and $|K^0_L\rangle$ would also be *CP eigenstates* ($|K_1\rangle$ and $|K_2\rangle$); with respective CP eigenvalues of +1 and -1. We show this below, via a CP transformation on Equations 3 and 4 [15]:

$$CP|K^0_s\rangle = \frac{1}{\sqrt{2}}\left[-|\bar{K^0}\rangle + |K^0\rangle\right] = |K^0_s\rangle \tag{5}$$

$$CP|K^0_L\rangle = \frac{-1}{\sqrt{2}}\left[|\bar{K^0}\rangle + |K^0\rangle\right] = -|K^0_L\rangle \tag{6}$$

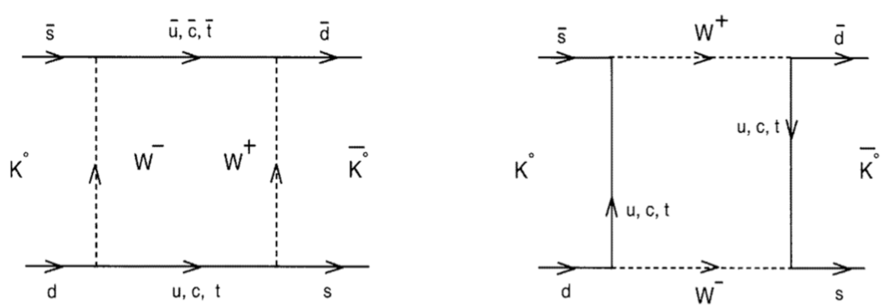

Figure 2: Box diagrams showing the oscillation of a K^0 meson into a $\bar{K^0}$ meson (LHS) and vice versa (RHS).

Under CP invariance, this would restrict the number of pions each neutral kaon could decay into [11] [14]. Consider a K^0_L meson decay producing two pions (a 2π decay), each with a CP eigenvalue of -1. Initial and final CP eigenvalues would respectively be -1 and $(-1)^2$; violating CP invariance since they are not equal. An equivalent argument is made if K^0_s mesons decay into three pions (a

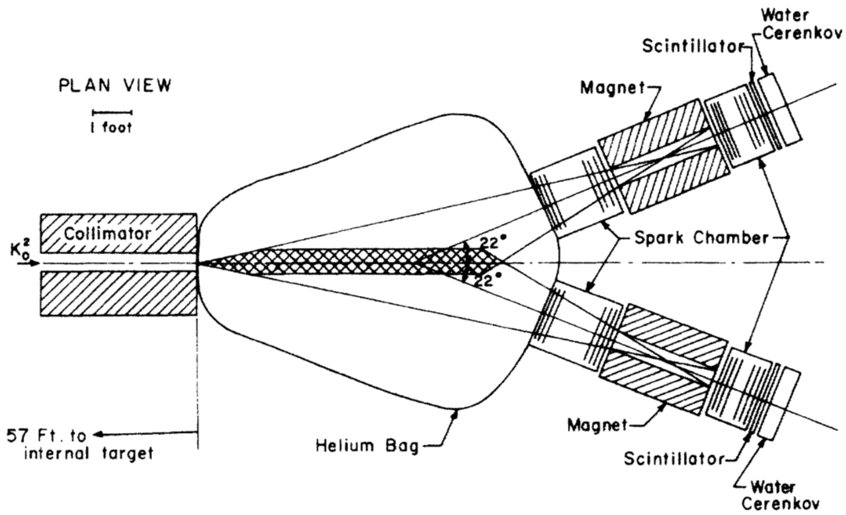

Figure 3: Diagram of experimental setup used by Cronin et al., where a K_0^2 beam is entering a collimator and a Helium filled bag. The decay products (pions) exit the helium bag and enter the detection equipment.

3π decay). This explains the expectation of Cronin et al., mentioned in the first report, [16] that K_L^0 mesons would not exhibit 2π decays.

Also mentioned was a disparity in K_s^0 and K_L^0 meson lifetimes. These differ by an approximate factor of 580, with respective values of 0.89×10^{-10} and 5.2×10^{-8} seconds [11] [14]. K_s^0 mesons therefore travel shorter distances before decay than their K_L^0 counterparts. Thus, K_L^0 decays can be isolated from a neutral kaon beam comprised of both long and short kaons (shown as K_0^2 Figure 3). Under CP invariance, these K_L^0 decays would be observed as 3π events. However, of the detected 22,700 decays were 45 ± 10 2π events [14] [17].

In the subsequent six months, Cronin et al. eliminated possibilities that this result was anomalous [18]. One such possibility was *coherent regeneration* of K_s^0 mesons in the Helium bag (Figure 3), resulting in additional 2π events. This effect involved producing K_s^0 mesons from pure K_L^0 mesons scattering in matter, as observed by Adair et al. [17] [18]. However, 10 of the 45 observed 2π events were attributed to this effect, discarding the possibility [11] [18].

To accommodate the remaining 35 2π events, $|K_s^0\rangle$ and $|K_L^0\rangle$ states were considered superpositions of CP eigenstates ($|K_1\rangle$ and $|K_2\rangle$), as opposed to pure eigenstates. This resulted in *indirect CP violation* and a phenomenological modification to Equations 3 and 4 [11] [15], where $|\epsilon|$ was found experimentally as $(2.23 \pm 0.01) \times 10^{-3}$ [19]:

$$|K_s^0\rangle = |K_1\rangle + \epsilon|K_2\rangle = p|K^0\rangle + q|\bar{K}^0\rangle \tag{7}$$

$$|K_L^0\rangle = |K_2\rangle + \epsilon|K_1\rangle = p|K^0\rangle - q|\bar{K}^0\rangle \tag{8}$$

Where p and q are defined as follows:

$$p = \frac{1+\epsilon}{\sqrt{2(1+|\epsilon|^2)}} \tag{9}$$

$$p = \frac{1-\epsilon}{\sqrt{2(1+|\epsilon|^2)}} \tag{10}$$

This is in contrast to *direct CP violation*, where a $|K_L^0\rangle$ meson directly produces a 2π event [11]; this prompted the 1980 Nobel Prize being jointly awarded to Cronin and Fitch [18].

Subsequently, the discovery led to predictions of new particles [20] and was postulated as one of three conditions for the existence of baryon asymmetry (BA, or matter-antimatter imbalance) by Sakharov in 1967 [21]. In the next sections, we discuss further implications of both this experiment and its predecessor.

4 Implications of The Wu & Fitch-Cronin Experiments

The results of the Wu experiment were unexpected; they showed that parity was not conserved in the weak interaction. This was fundamentally significant with regards to symmetry, as the parity violation differentiated between concepts of left and right. Since many interactions in nature are symmetrical with regards to left and right, such as in electromagnetic and gravitational interactions, the labels right and left (or North and South) are conventions that have been accepted. However, the labels can be swapped, and no experimental change would be observed. In the Wu experiment, the asymmetry meant that the conventionally named North and South poles of the Cobalt nuclei were intrinsically different, as one end consistently had a higher radiation intensity. For the first time, the distinctions between left and right (and the poles) were defined by intrinsic differences and not by convention [22].

The Wu experiment led to the evidence of CP violation and similarly, the Fitch-Cronin experiment also distinguished a distinction between two properties. The small surplus of positron decays and resulting CP violation indicates the existence of BA, which may be the reason for the imbalanced ratio of matter and antimatter in the universe. In this experiment, the amount of CP violation is too small to fully support this idea, so more must be detected. Furthermore, CP violation has since been observed in quark oscillations and weak interactions of B mesons [23]. As previously mentioned, in 1967 Andrei Sakharov proposed three conditions for BA [21], one of which was CP violation. He suggested that during the first few seconds of the Big Bang, there was asymmetry and so CP violation. This would support the asymmetrical matter-antimatter ratio, which was hypothesised to have been caused by baryogenesis.

The Fitch-Cronin experiment led to further discoveries. In 1972, Maskawa et al. worked on explaining CP violation in the Standard Model, which consisted of two generations of fundamental particles at the time (the up, down and strange quarks). This introduced the Cabibbo-Kobayashi-Maskawa matrix (CKM matrix), modelling flavour mixing in weak interactions. This theory contained three generations of quarks, which would allow CP violation to occur rarely, via quantum mixing [24]. These conclusions were confirmed by several experiments, including the discoveries of charm quarks in 1974[25], bottom quarks in 1977 [26], and top quarks in 1995 [27]. The physical applications of these experiments' results are next discussed further.

5 A Physical Example of Symmetry Breaking

As discussed in our previous report [16], chiral particles are those that cannot be superimposed onto their mirror image. It is also true that enantiomers can possess vastly differing properties. We have also introduced the concept of broken symmetry, where homochirality of certain particles and molecular structures occurs within the universe. In particular, local imbalances of the near racemic L and D-form amino acids in meteorite strikes on ancient Earth [28] was enantioenriched through a chemical amplification process [29]. The replication of primordial, non-cellular RNA from amino acids occurred due to a periodic drive from hydrogen peroxide [30], which is itself the simplest and smallest chiral molecule. Hydrogen peroxide [31] and amino acids [32] have been shown to exist in the interstellar medium, explaining their presence in the primordial soup. We can thus invoke Curie's principle to suggest that chiral asymmetry of hydrogen peroxide lead to homochiral RNA. This demonstrates symmetry breaking on a local scale and can theoretically have a mirror world existing simultaneously elsewhere in the same vector space.

Conversely, other symmetry breaking phenomena occur on a universal scale; one such asymmetry is that of matter and antimatter. Through analysis of the omnipresent Cosmic Background Radiation (CMB) [33], it has been shown that the early universe was hot enough for pair-production and annihilation to maintain a thermal equilibrium that kept the universe racemic [34]. The theory of cosmic inflation, which seems necessary to explain isotropy of CMB, would have diluted any pre-existing BA to negligible levels. Combining these theories gives the prediction that the initial baryon number was $B = 0$. Thus, a baryogenesis event must have occurred during either the reheating or radiation-dominated epochs for the universe to end in the current state of $B \neq 0$. As previously mentioned, Sakharov formulated 3 conditions that must be true for baryogenesis to be possible [21]:

1. The universe cannot be in thermal equilibrium

2. C and CP violation is possible

3. Baryon number violation is possible

The first condition can be understood intuitively as thermal equilibrium is, by definition, a state with time translation invariance. Hence the expectation values must be constants for all observables. This would not allow for evolution from B = 0 to $B \neq 0$. Mathematically, this can be demonstrated as:

$$\forall\Psi, \forall\hat{Q},\ \left\langle \Psi \middle| \hat{Q} \middle| \Psi \right\rangle = constant \tag{11}$$

Where Ψ is the eigenfunction of corresponding observable, $\hat{Q}$ is the operator that yields the eigenvalue that is the observable in question. It is intuitive to see this is not true. The second has been discussed in previous sections. The third, however, is a subject of theory, though one can easily see that it is a necessary condition to evolve from $B = 0$ to $B \neq 0$. It is theorised that baryon number violation is in fact possible through the sphaleron process [35]. A sphaleron is a non-perturbative solution to the time-independent electroweak field equations of the Standard Model [36]. Geometrically, a sphaleron would exist as a saddle point - in an infinite dimensional field space - of the electroweak potential. This is visualised in Figure 4. The minima either side of this saddle barrier represent two possible states for a particle. Each state has corresponding baryon number. Classically, should a particle be given enough energy, it can cross the barrier; these are called sphaleron particles. For the sphaleron process to have a probability higher than ~ 0, the energies must be extremely high, which would have been the case in the early stages of the universe [34]. There is also another theoretical process for breaching this potential barrier. Using notions from Quantum Field Theory (QFT), it is theoretically possible for a particle to tunnel through the barrier, thus being able to change states at lower energies than classically possible. This process is called an instanton and represents the solution to the equations of motion in QFT [37].

A common example of a sphaleron would be where one minimum contains 3 antileptons, and the other, three baryons. This would allow for a process that transforms $B = 0$ to $B = 3$ and vice versa. Such a symmetry-breaking, theoretical process could indeed be the vehicle for baryogenesis[38].

In conclusion, it is theoretically possible to satisfy all three of Sakharov's conditions for baryogenesis. This means that even if the universe started of with $B = 0$, during its evolution, through symmetry breaking processes, baryons were able to dominate antibaryons. Thus, upon the cooling of the universe, the matter and anti-matter annihilated into photons, leaving predominantly matter, which was in excess. It is possible that this is how the universe has achieved this matter dominated state.

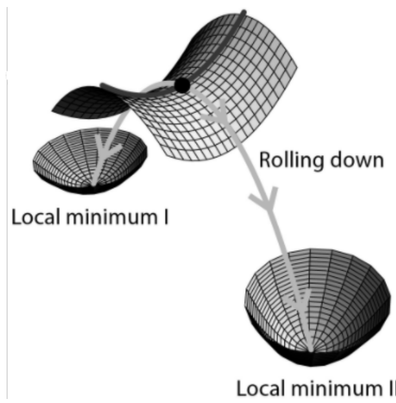

Figure 4: Geographical interpretation of sphaleron as saddle point with two local minima.

6 Conclusion

It has been shown in this report that the C and CP symmetries we once considered invariant, are in fact demonstrably violated in the electroweak interaction. Furthermore, there is now an explicit way of distinguishing between chiral states, which implicitly results in their varying properties. This has been shown to lead to local scale symmetry breaking such as DNA homochirality. Comparably, it can also lead to symmetry breaking on a universal scale, as discussed with regards to baryogenesis. It should be noted that further research into symmetry breaking should be conducted, especially at high energies, which may well lead to significant predictions. In the past, predictions based of symmetry breaking have led to proven predictions such as existence of particles; a famous example of this was the discovery of the Higgs Boson [39].

To Conclude, as shown by the Fitch-Cronin experiment, the violation events are rare, and so patience and perseverance are pivotal for the progress of the field of discrete symmetry.

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A Contributions

Every group member (with the notable exception of Diana Temiseva) has made an equitable contribution to this report.

Robert William Sterling: I wrote the section titled *A Physical Example of Symmetry Breaking*. I co-wrote the abstract and conclusion. I proof read, edited, finalised and formated the report.

Francesca Panteli: I wrote section three, *The Fitch-Cronin Experiment Revisited*. I also co-wrote the abstract and conclusion. Furthermore, I proofread the report to ensure cohesion between sections. I made a Teams group and shared One Drive folder.

Yasmin Yau: In this report, I wrote the section one, *Implications of The Wu Fitch-Cronin Experiments*. I also co-wrote the abstract and conclusion as well as proofread the read the report for potential mistakes.

Omar Salama: I wrote the section two, Results from The Wu Experiment Subsequent Experiments. It was my sole duty to ensure morale was well above satisfactory.

Kush Shah: I wrote section one, *Background Theory for The Wu Experiment*. I brainstormed ideas and a made a mindmap.