On the Discovery of Parity Violation

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1 Background

The power of scientific reasoning is that it forces us to shed ourselves of our bias perceptions of nature as human beings, and encourages us to discover the truth. However, sometimes scientific reasoning leads us to truths which are so commonplace that we put *too* much faith in them. Symmetry in nature has long been part of the appeal of physics. Human lives are complicated, and people have a tendency to perceive the world as being an overly complex place. The power of physics to simplify and unify the phenomena around us has a soothing effect on us all. Simplification and Unification are examples of truths which we have come to expect. Newton unified Heaven and Earth through his theory of Gravitation, Einstein unified the idea of mass with energy, gravitational mass with inertial mass, as well as physics with geometry. The list goes on, but in the early 1950's, scientific reasoning lead Lee and Yang to reconsider one of the most successful and long believed in symmetries of nature–that of parity.

Parity is also known as mirror symmetry, or left-right symmetry. To say that nature exhibits mirror symmetry, or invariance under parity, is to say that if a phenomenon is known to occur, then the mirror image of that phenomenon can also occur in nature equally often. Parity offers an excellent example of the power of scientific reasoning to shed us of our human bias. Parity invariance is not an obvious fact for human beings, since everyone knows there is a majority of right handed people in the world, and that cars (in Canada) drive on the right hand side of the road, and that English is written from left to write, etc. But scientific reasoning allows us to recognize that all of these examples have historical reasons behind them: in many countries cars drive on the left hand side, and languages such as Arabic are read from right to left. However, for more general phenomena, like collisions of particles, there is no obvious historical reason why nature would not allow for both left hand and right hand versions to occur, and so before the 1950's, parity invariance was a seemingly obvious symmetry of nature to physicists.

2 Tau-Theta Puzzle

What happened to this beautiful and well established symmetry of nature? The downfall of parity invariance began in the early 1950's with a problem known as the Tau-Theta Puzzle. At the time there were two particles called the τ and θ particles. These particles appeared to be identical in every way–same mass, spin, charge, etc–however, they exhibited different decay modes, mediated by the weak interaction:

$$\theta^+ \rightarrow \pi^+ + \pi^0$$
$$\tau^+ \rightarrow \pi^+ + \pi^0 + \pi^-$$

To understand the puzzle, you need to know that particles can be assigned a value of "parity", +1 or -1, depending on how they behave under the operation of mirror inversion. If nature exhibits parity invariance, then the value of parity is conserved in a reaction. So here's the puzzle: the products in these two reactions have opposite parity, and since at the time parity conservation was a sacred symmetry of nature, the logical thing to conclude is that nature created two particles that are almost identical in every way, except with opposite parities. To physicists at the time, this just seemed wasteful, and it was not clear why nature would allow for it.

This is what motivated Lee and Yang to consider the possibility that the two particles were in fact one and the same (yet another example of "unification" in physics). However, this would require that parity is not conserved in the weak interaction. At the time, this was a big statement, and so Lee and Yang poured over the scientific literature to find if any *experimental* evidence for parity conservation in the weak interaction existed, and they found that no experimental tests had been carried out. Lee and Yang proposed a number of experimental tests for parity conservation in the weak interaction, and in the same year such an experiment was carried out by Wu which confirmed parity *violation* in the weak interaction.

Our lives are predominantly governed by the electromagnetic and gravitational interactions, forces of nature which *do* exhibit mirror symmetry, and so it makes sense that parity conservation is intuitive to us, but evidently this does not hold true in the weak case.

3 Beta Decay

One experiment suggested by Lee and Yang involved beta decay, and was carried out by Wu. Beta decay is mediated by the weak interaction and involves the transformation of a neutron into a proton, or visa versa, and the creation of an electron and neutrino. Beta decay of a nucleus can be used as a test of parity conservation when the magnetic moment of the nucleus is polarized in the z-direction. To understand how this comes about, we describe the physics of this system.

The magnetic moment of the nucleus is polarized in the z-direction using a magnetic field. When the nucleus undergoes beta decay, it will liberate an electron which will fly out of the nucleus at a certain angle, and that is the end of the interaction. To see why this is relevant to parity, we look at the mirror image

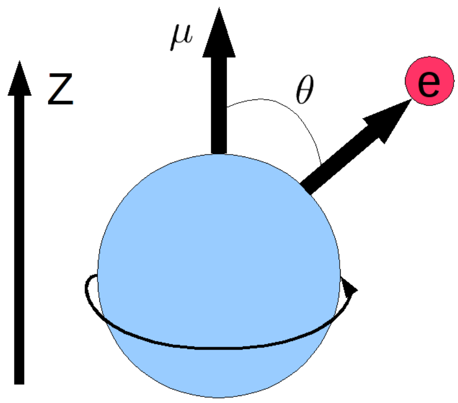

Figure 1: Beta decay of a nucleus (blue circle). The magnetic moment is drawn according to the right hand rule, and the spin of the nucleus is suggested by the looping arrow. The electron (red circle) has a velocity with angle θ w.r.t. the magnetic moment, μ.

of the same system. In the mirror, the electron flies out of the nucleus at the same angle to the positive z-axis; however, in the mirror the nucleus is spinning the other way around, and so its magnetic moment is now in the *negative* z-direction. This means that the angle between the trajectory of the electron and the magnetic moment of the nucleus has changed. To be precise, if the magnetic moment is pointing in the z-direction, and it is found that the angle between the electron trajectory and the positive z-axis is θ, then in the mirror the angle between the two is $(\pi - \theta)$. Therefore, if parity is a true symmetry of nature, then both angles of θ and $(\pi - \theta)$ should be observed equally often. The experiment by Wu shows that this is *not* true, and in fact one of these angles is favoured by nature. It turns out that electrons leave the nucleus preferentially *away* from the magnetic moment, ie. $\frac{\pi}{2} < \theta < \pi$.

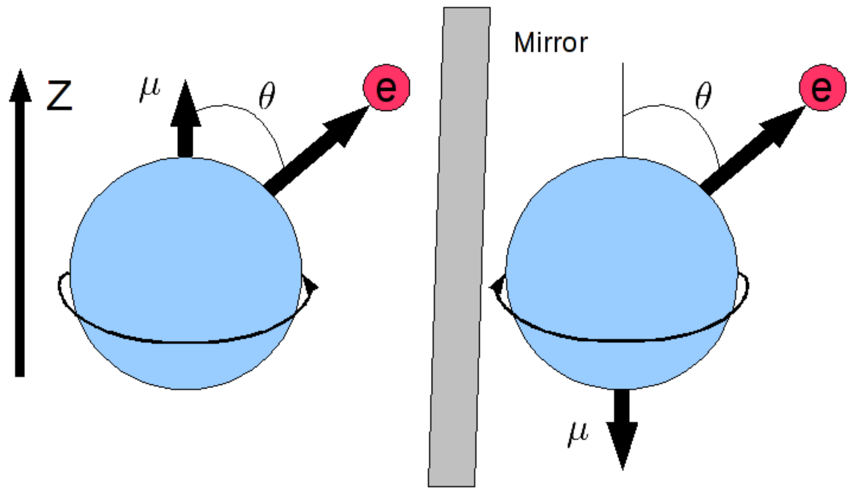

Figure 2: Beta decay in the mirror. In the mirror the nucleus now spins in the opposite direction, as indicated by the looping arrow, and the direction of the magnetic moment, μ, flips to the negative z-direction. Thus the angle between the electron trajectory and the magnetic moment changes.

4 Experiment 1: Beta Decay of Co^{60}

Wu used Cobalt-60 nuclei to observe parity violation in beta decay. Cobalt-60 was chosen because an experimental method for magnetically polarizing the nuclei was already well known at the time, the Rose-Gorter method. Cobalt-60 decays into Nickel-60 through negative beta decay, which converts a neutron into a proton, given by:

$$n^0 \rightarrow p^+ + e^- + \overline{\nu}_e$$

The Ni^{60} is produced in an excited state, and quickly relaxes by emitting two gamma rays. When the Rose-Gorter method is applied, the direction at which the gamma rays exit the Ni nucleus is correlated to its magnetic moment, and so in the experiment done by Wu, Co^{60} is magnetically polarized in the z-direction using magnetic fields, and this polarization can be checked by detecting the exiting gamma rays. To implement this check, Wu used two NaI scintillators placed at the predicted angles for polarization along the z-axis, as seen in the figure.

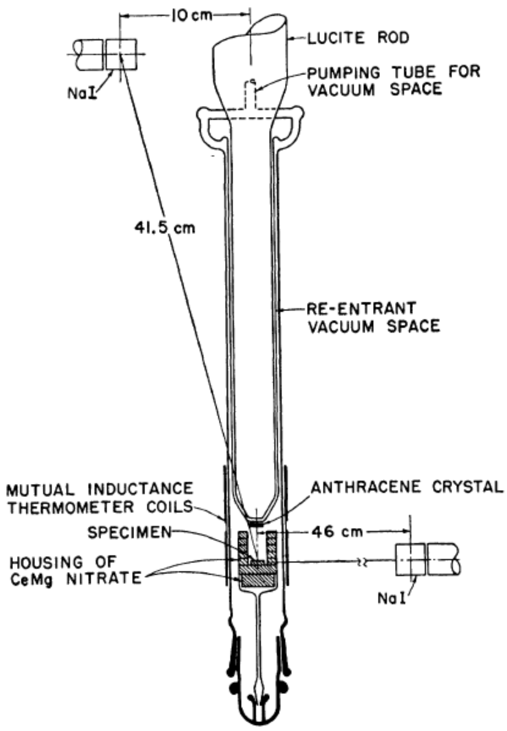

Figure 3: The apparatus used by Wu, taken from her original paper.

To detect the beta particles, an anthracene crystal is placed about 2 cm above the Co^{60} source. Scintillations from the crystal are passed through a Lucite light pipe towards a photomultiplier tube for detection. The end of the lucite pipe at the crystal/pipe interface is machined into a logarithmic spiral shape for maximum light collection.

By comparing the detection rate of beta particles when the Co^{60} nuclei are polarized in the positive z-direction to when they are polarized in the negative z-direction, an anisotropy was found, indicating a violation of parity, see figure 4. Although it was difficult in this experiment to quantify the amount of asymmetry, Wu estimated that nearly 70% of all emitted electrons exited away from the direction of the magnetic moment. That's a *big* difference!

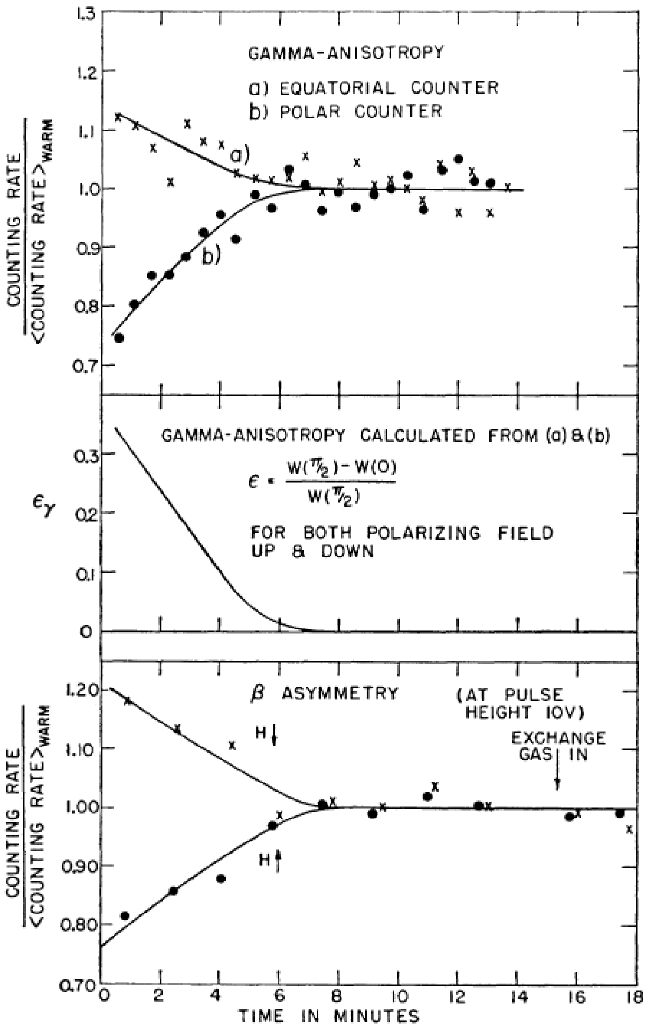

Figure 4: Wu's results, taken from her original paper. The top graph shows the output of the NaI detectors as the sample depolarizes. The splitting of the curves results because the Rose-Gorter method causes an anisotropy in the gamma ray emissions, which disappears as the magnetization vanishes. The bottom graph shows the beta particle detections. Here the splitting occurs due to parity violation. Note that the gamma and beta anisotropy vanishes at the same time, which is the expected behaviour.

5 Pion Decay

Prior to publishing his results, news of Wu's success in observing parity violation in beta decay reached the ears of another group of experimentalists (Garwin, Lederman, Weinrich). This encouraged the group to design an experiment to look for parity violation in one of the other systems suggested by Lee and Yang. They chose to investigate the successive reactions:

$$\pi^+ \to \mu^+ + \nu$$
$$\mu^+ \to e^+ + 2\nu$$

This system can test parity violation because Lee and Yang had shown that if parity is violated, then there would be an asymmetry in the polarization of the μ along the direction of motion. Furthermore, one can use the angular distribution of electrons emitted from the second reaction to determine experimentally what the μ polarization is.

6 Experiment 2: Magnetic Moment of the μ

The experimental setup is shown in figure 5. The π particles were produced using a cyclotron, and were stopped in an 8-in of carbon. The thickness was chosen in order to stop as many π as possible, and was calculated based on the energies which were produced in the cyclotron.

The μ produced in the first decay leaves the carbon absorber and is stopped in another carbon target. An electron microscope is placed at an angle of 100° with respect to the carbon target in order to detect the electrons produced in the second decay. Note that the detector is *fixed*, and so in order to measure the angular distribution of electrons emitted from the μ source, it is necessary to rotate the magnetic moment of the μ by applying a magnetic field. This is achieved by wrapping a coil around the carbon target, and applying a direct current. By increasing the current, a larger range of angles can be measured, and so the current can be tuned as required.

A typical run at fixed current is shown in figure 6. By inspection one can see that there is an asymmetry in the angular distribution of electrons, and thus evidence for parity violation in this system. The angular distribution was found to have the form $1 + a\ cos\theta$ and it was found that $a = -\frac{1}{3}$ for the stopped μ^+.

The same experiment was also carried out for the system:

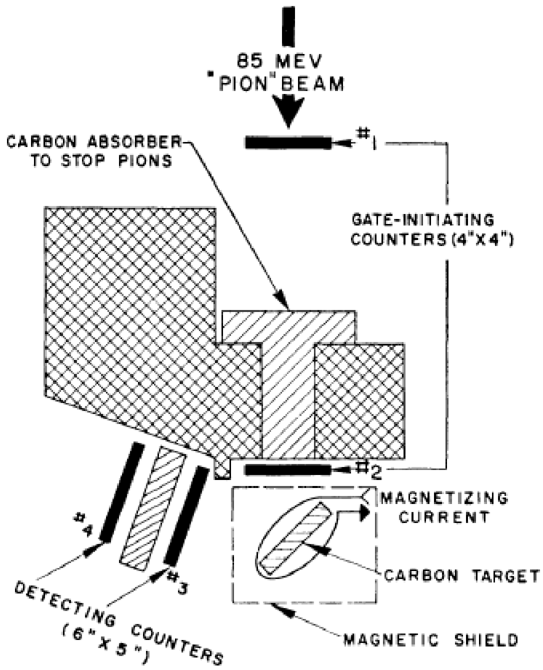

Figure 5: The apparatus used by Garwin, taken from his original paper. Pions from the cyclotron are stopped in the carbon absorber, and muons created in their subsequent decay are stopped in the carbon target.

$$\pi^- \rightarrow \mu^- + \overline{\nu}$$

$$\mu^- \rightarrow e^- + 2\nu$$

so that now μ^- are stopped in the carbon target. For the μ^- it was found that $a = -\frac{1}{20}$. An explanation is not provided by the experimenters as to the underlying reason why the two systems vary so much, but in both cases it is clear that parity is being violated.

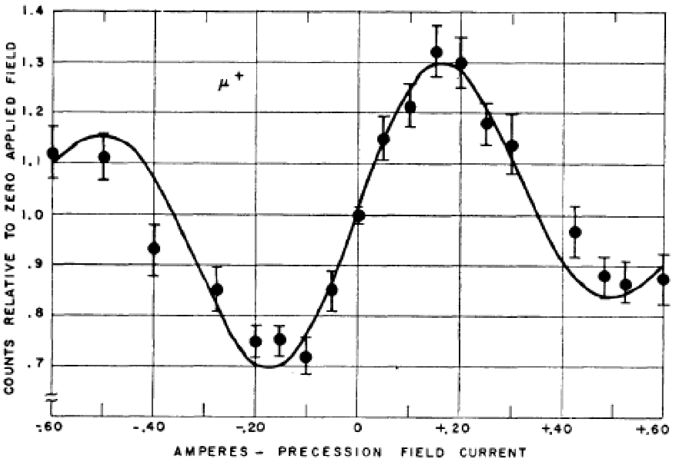

Figure 6: Increasing the current in the loop causes the stopped muons to rotate their magnetic moments more, and the electron distribution is thus sampled at a different angle. By increasing the current to see the whole range of angles, an anisotropy is observed.

7 Summary

The tau-theta puzzle, involving particle decays through the weak interaction, caused Lee and Yang to question for the first time the possibility of parity violation, a long held symmetry of nature. Experimentation was quickly carried out by both Wu and Garwin et al to confirm that parity is violated in the weak interaction, namely in the beta decay of Co^{60} and in the decay of the π particles. This is an unsettling conclusion, because the historical trend of physics up to this point was one of simplification and unification; that although the mathematical description of phenomena may become increasingly complicated, nature seemed to always become more symmetrical and more interconnected than previously thought. In the case of parity violation, however, we learn that nature exhibits a very striking asymmetry for no apparent reason, and goes against our expectation of a symmetrical universe.

8 Future Outlook

The work of Lee and Yang, Wu, and Garwin et al has provided definitive proof that mirror symmetry is broken in the weak interaction, and so we can say that mirror symmetry is *not* a true symmetry of the Universe as a whole. However, mirror symmetry is a *good* symmetry for the electromagnetic interaction, gravity, and the strong interaction. Beyond the weak interaction, it is such a good symmetry that it might be tempting to consider that the breaking of parity in the weak interaction is somehow balanced by an opposite breaking of parity somewhere else in physics, and we simply have not discovered this physics yet.

Theorists have considered what kind of physics would be required to restore mirror symmetry to the Universe. In particular, mirror symmetry can be restored if there exist so called "mirror particles". It has been shown that mirror particles would interact very weakly with ordinary matter, except through the gravitational force. This has to do with the force mediators; it has been shown that mirror matter would interact through mirror bosons, and that none of the known bosons, besides the graviton, can be identical to their mirror partners. The fact that we have not observed the mirror force mediators means that they are too massive for us to produce, assuming they exist at all.

For this reason mirror particles are one candidate for the dark matter of the Universe. If mirror particles exist in sufficient abundance, we might detect them through their gravitational effects. Also, Sheldon Glashow has shown that if ordinary matter and mirror matter interact at some high energy scale, then there would be radiative corrections which lead to mixing of photons and mirror photons. One of the predicted effects of this mixing is that it would cause an oscillation between positronium and mirror positronium. This would allow for positronium to turn into mirror positronium, and then decay into mirror photons.

Experiments for detecting mirror particles are currently being planned, so for the time being we will have to accept that the Universe simply does not exhibit mirror symmetry, and that the experiments concur with this. It is definitely true that parity is not conserved in the weak interactions of ordinary matter, and this will always be true no matter how much we want to believe that the Universe should be more symmetric.