The Particle that Violates the Symmetry of Nature

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Symmetry in the Standard Model

Matter is what makes us up, as well as everything else we see and feel, from cats in boxes to fundamental particles like electrons. But in the 1930s, physicists discovered the existence of antimatter: an exotic substance characterised by having the same properties as normal matter, but with an opposite electric charge. In theory, this could make up the same things as we see – anti-cats in anti-boxes to anti-electrons (also called positrons). However, an important problem in physics is to know how exactly this antimatter behaves. And more specifically, if the laws of physics governing both types of matter are the same, or if there are small subtleties that distinguish them? Do the two simply just differ by their charge, and nothing else? I.e. if we built a machine that could turn your cat into an anti-cat, would it physically behave the same way as it did before?

What essentially underlies this question is the notion of symmetry. If a system satisfies a symmetry, it means that it does not change under some transformation: e.g. by a rotation or translation. Noether's theorem describes that for every symmetry in a system, there is a corresponding conservation law, which is why determining symmetries becomes essential when researching physics [1]. Without any derivations, we can know that if a system satisfies translational symmetry, then momentum is conserved. Similarly, rotational symmetry leads to conservation of angular momentum, and in fact time-translational symmetry corresponds to mass-energy conservation. Most importantly, Noether's theorem is valid for any specific kind of system. It could be for a single particle, a cat in a box or the entire universe!

> “ *It is only slightly overstating the case to say that physics is the study of symmetry.*
>
> Philip Anderson, *1972*

One obvious symmetry that we can observe between matter and antimatter is obtained by flipping the charge, since for example giving a negatively charged electron a positive charge, turns it into a positron. We call this charge-conjugation symmetry, or *C-symmetry*, and it is one of the discrete near-symmetries of the Standard Model illustrated on Figure 1 [2]. Discrete, because it describes a 'sudden' change, in contrast to continuous symmetries such as smoothly rotating a circle around its origin. And only nearly symmetric because, as we will discuss later that, some particles actually violate it.

There also exists two other discrete transformations linked to the particle's position in space and time itself, which we can manipulate. Parity symmetry, also called *P-symmetry*, is obtained by inverting the position of all the particles in space in some coordinate system. If we imagine enormous x-, y-, and z-axes embedded into space, this corresponds to mirroring all points around the origin. What matters is not where the origin itself is located, but that 'right-handed' and 'left-handed' configurations are swapped, just like when looking into a mirror and seeing your mirror self being dominant with opposite hand.

Lastly, we obtain another transformation by reversing the direction of time, called *T-symmetry*. Though time-symmetry might seem counter-intuitive, the second law of thermodynamics tells us that the total entropy never decreases in the forwards direction of time for non-reversible processes. So if we were to travel backwards in time, we should measure a decrease in entropy.

A truly T-symmetric system would therefore be one where all the processes happening in it are reversible, such that the total entropy remains constant [3]. And oh look, we just found a conservation law! In fact, a T-symmetrical system is exactly one where entropy remains constant.

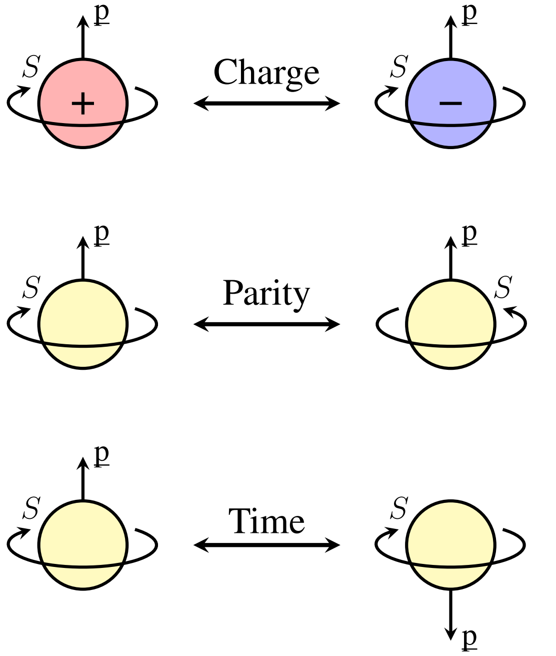

Figure 1: Illustration of the changes a particle undergoes via the three different discrete symmetries, where S is the spin and $\underline{p}$ is the momentum vector.

It should not be a surprise to the reader that we can construct new transformations and symmetries from others. Imagine flipping the charge and position at the same time. This combined symmetry, which we will call CP, has a new conservation law linked to it, that is different from both C and P. Also note that CP-symmetric systems do not necessarily need to be either C- or P-symmetric. If a system violates both C and P in equal and opposite ways, combining these could lead to a non-violated CP-symmetry [4].

But let us not stop here. What if we combine all three of the mentioned transformations into one symmetry, CPT? Applying this to e.g. the entire universe, would first of all swap all particles with their antiparticles, invert their positions, and make time run backwards. It's the complete opposite – an "anti-universe" – of what we live in. And like any other symmetry, CPT also has an associated conservation law, which turns out to be Lorentz invariance: the proposition of special relativity that physics behaves the same way for all moving observers within an inertial frame [5]. Not only is Lorentz symmetry well-established in relativistic physics, but all experimental attempts to disprove it so far have failed. So if Lorentz invariance holds true throughout the entire universe, does that also mean the universe itself is CPT-symmetric? Neither is this an easy thought experiment or easy to prove, but it plays a founding role in the so-called *CPT theorem*. It states that any physical theory we know, or might develop in the future, that is Lorentz invariant, must also be CPT-symmetric [2].

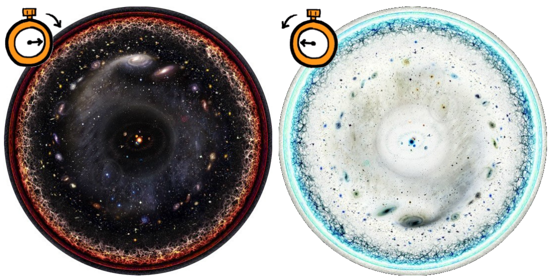

Figure 2: Our universe and its CPT equivalent: where position is inverted, time runs backwards, and particles become antiparticles – what a weird place to be.

Breaking Symmetry

For a long time it was thought that the Standard Model and the fundamental forces, besides satisfying CPT, must also be C-, P- and T-symmetric respectively. As an example, if we simply swap all particles with their antiparticles, i.e. apply a C-transformation, and look at the electric and magnetic fields, both would point in reverse directions. However the dynamics of all the particles in these fields would still be preserved [3]. Hence, the electromagnetic force must be C-symmetric. The same idea went for all other forces, but during the 1950s, clues in particle physics suggested that maybe C, P, and T were not true symmetries in the Standard Model.

Neutrinos are fermionic particles with zero electric charge. It is a fact that only left-handed fermions and right-handed antifermions interact through the weak nuclear force [2]. What is meant by the "handedness", also called *chirality*, relates to the direction of the particle's spin relative to its momentum. If they point in the same direction we call its chirality 'right-handed' and opposite directions is called 'left-handed'.

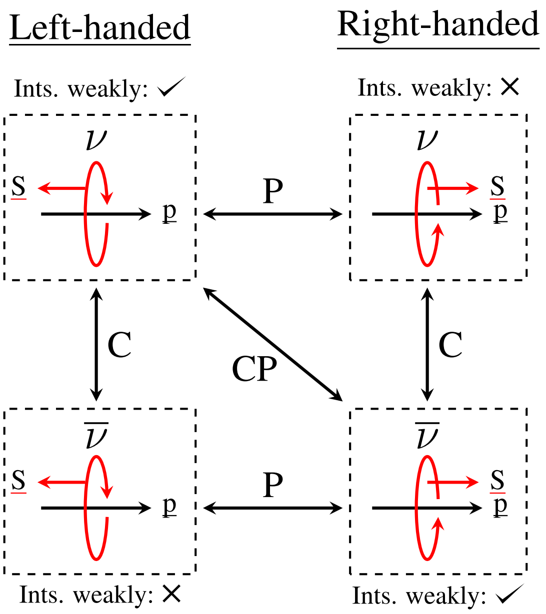

Figure 3: Schematic diagram of how the neutrino and antineutrino particles relate under C- and P-transformations. Only the CP pairs obey the symmetry with respect to the weak force.

As seen on Figure 3, the direction of the neutrino spin and hence its chirality is invariant under a C-transformation. A left-handed neutrino would therefore be turned into a left-handed antineutrino. But whereas the left-handed neutrino interacts through the weak nuclear force, the left-handed antineutrino does not – a maximal violation of C-symmetry! For the first time in history, one of the three symmetries that before were believed to never be broken, seemed to easily shatter regarding neutrinos and their weak interactions.

It was not yet obvious *why* either the neutrino or weak interaction broke C-symmetry. So around 1956, verifying the other symmetries for all the fundamental forces became a major topic in physics. Tsung-Dao Lee and Chen-Ning Yang pointed out that no experiments had actually confirmed or disproved P-symmetry in relation to the weak nuclear force [6]. That same year, Chien-Shiung Wu and her team conducted an experiment where they at low temperatures aligned the spins of radioactive ^{60}Co atoms in a magnetic field, and measured the directional properties of the emitted beta decay [7, 8]. Figure 4 illustrates how the solenoid that generated the magnetic field could be inverted, creating a P-symmetrical version of the experiment.

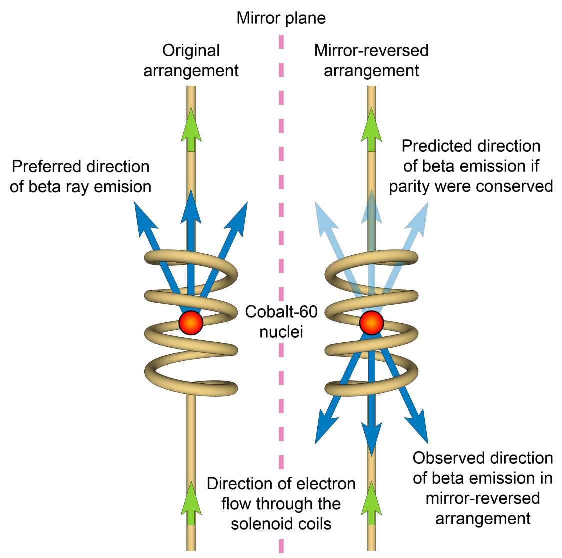

Figure 4: The principle of the Wu experiment in 1956, where the direction of beta decay from ^{60}Co atoms put in a magnetic field. The P-symmetrical experiment did not give the same results!

In the original setup, they found that electrons were primarily emitted in the direction opposite the ^{60}Co spin. If the weak force really obeys P-symmetry, a mirror image of such an experiment should not change the direction of emission. But what Wu found was that no matter what, electrons were emitted opposite the spin. Thus, the experiment proved that the weak force also violates P-symmetry.

The ambidextrous universe

The fact that the universe is neither C- or P-symmetric came as a great surprise, and was very controversial to many physicists. Wolfgang Pauli, after the release of Wu's results, insisted that the measurements were wrong and commented "That's total nonsense!" [8]. And in some way it is total nonsense... Because a P-transformed universe would be one where not only the chirality of particles is interchanged, but e.g. all right-handed people would become left-handed, just like when looking into a mirror. Now imagine an experiment where we wanted to determine if we lived in that mirror universe or not. Wu's experiment can be used for exactly that purpose! *Left* and *right* are not simply conventional labels, but distinct directions that nature itself can distinguish. In his book, 'The Ambidextrous universe' by Martin Gardner, he poses the so-called *Ozma problem*, questioning how humanity could, upon contacting an alien civilisation, convey the difference between left and right [9]. P-violation proposes a solution to exactly this. If the aliens were instructed to build Wu's experiment, they could determine the directions based on their results.

But maybe it is all right if C and P are violated. Both the neutrino-asymmetry and Wu's experiment violate either C or P, but become symmetric when applying the other. So even though the symmetries seem logical by themselves, what if they are just part of some greater collective symmetry, CP, which instead cannot be violated?

The particle that violates the symmetry of nature

Not many years after Wu's discovery, James Cronin and Val Fitch were set to test whether CP was indeed a universal symmetry or not. More specifically, they studied the decays in neutrally charged kaon particles, K^0 and its antiparticle $\overline{K}^0$. It was already well-known that they decayed into either two or three pion particles, but at two very different rates [10].
Let us try to imagine what would happen to that decay, *if* it obeyed CP-symmetry. First consider the CP-transformation as a quantum mechanical operator that flips the parity and charge of the particles. It can be shown that K^0 and $\overline{K}^0$ are not actually eigenstates of the CP-operator, but their superpositions

$$K_1 = \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0)$$

and

$$K_2 = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0)$$

are, with eigenvalues $+1$ and -1 respectively [11, 12]. Furthermore, one pion has a CP eigenvalue of -1, hence n pions has eigenvalue $(-1)^n$. Fitting all the puzzle pieces together, the total eigenvalue before and after the decay must stay constant to preserve the symmetry. Thus, K_1 must decay into two pions, and K_2 decays into three pions, which is sketched on Figure 5.

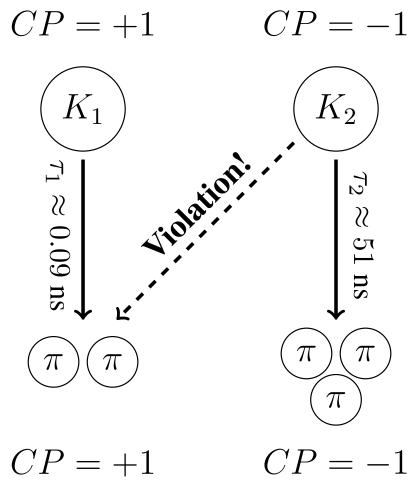

Figure 5: Diagram of the kaon particle decays that satisfy CP-symmetry by matching their CP eigenvalues. A decay that changes the eigenvalue would lead to direct CP-violation.

The two types of decays are associated to each their mean lifetime τ. Theoretically, it can be found that K_1 must correspond to a short-lived kaon that has a mean lifetime roughly 600 times shorter than K_2 [13]. In the famous Fitch-Cronin experiment [14], kaons were emitted through a long tube, and their decays could be detected along it (see Figure 6). Far away, one would only expect to observe kaons decaying into three pions, and not two, because K_1 decays way before it can reach the detector. But what was observed was exactly the opposite. Even far away, pion pairs were observed amongst the decay into three pions. This meant that either they had observed very unlikely events, or the assumption that the CP eigenvalues were held constant was incorrect: K_2 could indeed decay into two pions. After repeated measurements, they confirmed that surely CP must have been violated, and were awarded a Nobel Prize for their discovery in 1980.

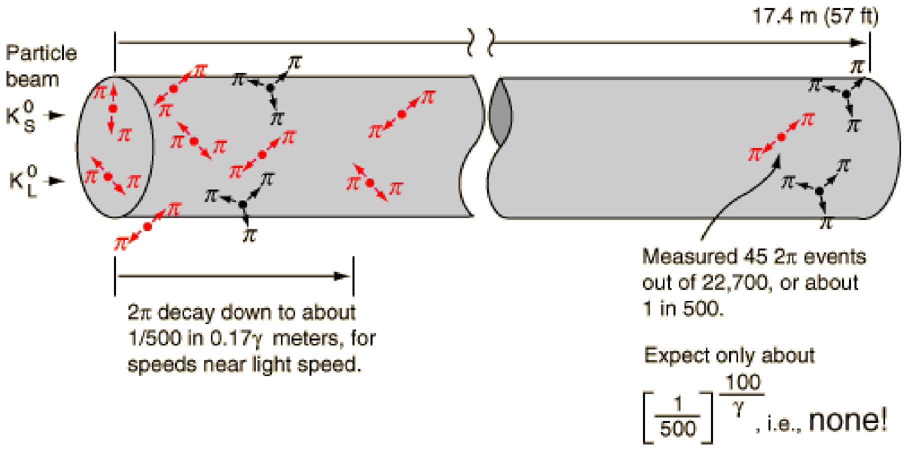

Figure 6: The Fitch-Cronin experiment consisting of a mix of long- and short-lived kaon particles being emitted through a long tube. The long-lived kaons violated the CP-symmetry by decaying into two pions instead of three, changing their CP eigenvalues [15].

All we need is time

Now let us collect and extrapolate upon the results we have discussed so far. C, P, as well as CP were all experimentally shown to be violated when involved with the weak nuclear force. All there is left to solve is T-symmetry. As a thought experiment, imagine a scenario where T is symmetrical. The addition of CP and T would definitely result in a violated symmetry because CP is violated. But the CPT theorem established that CPT has to be obeyed for relativity to be consistent. Then surely T-symmetry must also be violated, but in an equal and opposite manner to CP, for CPT to hold true [16].

Not to be mistaken with our initial example of T-symmetry and entropy conservation, T-asymmetry does not cause a violation of the laws of thermodynamics! If a process is reversible, but happens at different rates in each direction in time, entropy is constant but time is still violated – this does not interfere with thermodynamics. It leads us to the principle of Kabir for directly testing T-violation. Kabir proposes that by studying processes $A \to B$ with some probability of occurring, if the time-inverted process $B \to A$ then happens at a different rate, the interactions must be governed by T-violating laws [17, 18]. Of course we would prefer to be able to test this by magically flipping a switch that reverses the flow of time.

But as this proves to be very difficult (if not impossible) it only becomes relevant to study reversible processes that naturally occur in both directions. Lucky for us, even before Cronin and Fitch's experiment, a paper by Gell-Mann and Pais [19] pointed out that in the presence of weak interactions, our friends the neutral kaons, naturally oscillate between the two states $K^0 \rightleftarrows \overline{K}^0$. As we saw before, kaons violated CP-symmetry through the decay of their superpositions, so we also expect them to violate T-symmetry. It then becomes much simpler to test T-violation by applying Kabir's principle, as shown on Figure 7: if we observe $K^0 \to \overline{K}^0$ to occur at a different rate than $\overline{K}^0 \to K^0$, then the kaons violate T-symmetry! This was in fact confirmed at the CPLEAR detector at CERN in 1998 [20]. There was a noticeable asymmetry between the two processes, constituting to the first direct measurements of T-violation. Though Kabir's principle and T-violation reminds us a lot about the second law of thermodynamics, where processes have a *preferred* direction of moving through time, it remains an unanswered question if kaon oscillations relate to the macroscopic arrow of time. In theory, single particles violating T-symmetry could build a "quantum mechanical arrow of time", that somehow scales up to the laws we have already defined.

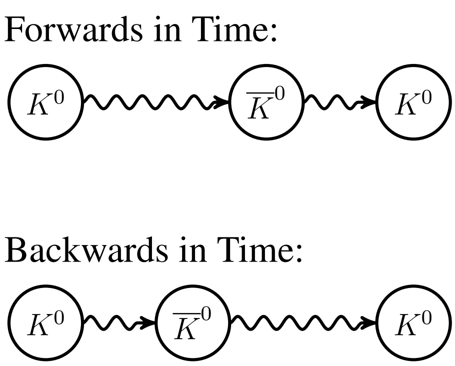

Figure 7: Kaon oscillation occurs differently if the direction of time is reversed. This illustrates how they break T-symmetry via Kabir's principle.

Does it even 'antimatter'?

A not so obvious consequence of CP violation lies in the matter antimatter asymmetry of the universe. The Big Bang should, according to our current knowledge, have created equal amounts of matter and antimatter in the early universe. But then how come, everywhere we look around us, from the dirt on Earth to all stars and galaxies, that everything purely consists of matter? Figure 3 sketched how CP is an operator that, in a stronger way compared to C, switches between particle and antiparticle, since it also corrects the chirality. The fact that both C and CP are violated must mean the laws of physics are definitely different for matter and antimatter! As of yet, we don't know exactly how this asymmetry ended up 'favouring' matter, allowing such an imbalance, but there are many candidate theories that are currently being proposed and tested.

One idea is that we live in a "patchwork universe": where space is split into different regions dominated by either matter or antimatter. Problem is that we have not observed any such places yet. Though there is the possibility of them existing far away from us, the boundaries between these regions would emit large amounts of light due to the annihilation processes occurring. Even at its lowest bounds, and considering the redshift due to the expansion of the universe, the light from these interfaces would still be visible today and contribute significantly to the background radiation [21]. It therefore seems very unlikely that there is *any* region within the observable universe that is dominated by antimatter.

A recent theory by Boyle, Finn and Turok proposes an even stronger solution to CP-violation, matter antimatter asymmetry, and even the origin of CPT symmetry [22, 23]. It suggests that the universe after the Big Bang is itself the CPT image of the universe before it. I.e. when the universe was created, it sent a matter-dominated universe in the forwards direction of time, leaving the remaining anti-matter in an anti-universe travelling backwards in time. The laws of physics in both universes would be the same, and the arrow of time would not move in just one direction, but simply 'diverge' from the origin $T = 0$. Curiously, the anti-universe would be inhabited by people made of antimatter also thinking they are made of "normal" matter. In fact, due to the CPT theorem, our universe would be indistinguishable from the anti-universe, by means of any physical experiment.

But of course there is also the possibility that CPT is, opposed to what we believe, actually violated. Throughout history, physicists were confident that charge-, parity- and time-symmetry were these unbreakable laws that the universe should obey. But as we gathered further insight, experiments have time after time proved that these symmetries were violated. Even CP became just a temporary solution. So all that is left to test is CPT – the ultimate symmetry which is deeply rooted into our current special relativity and quantum field theory. Is it truly unbreakable? Or will it fall and take all of modern physics with it?

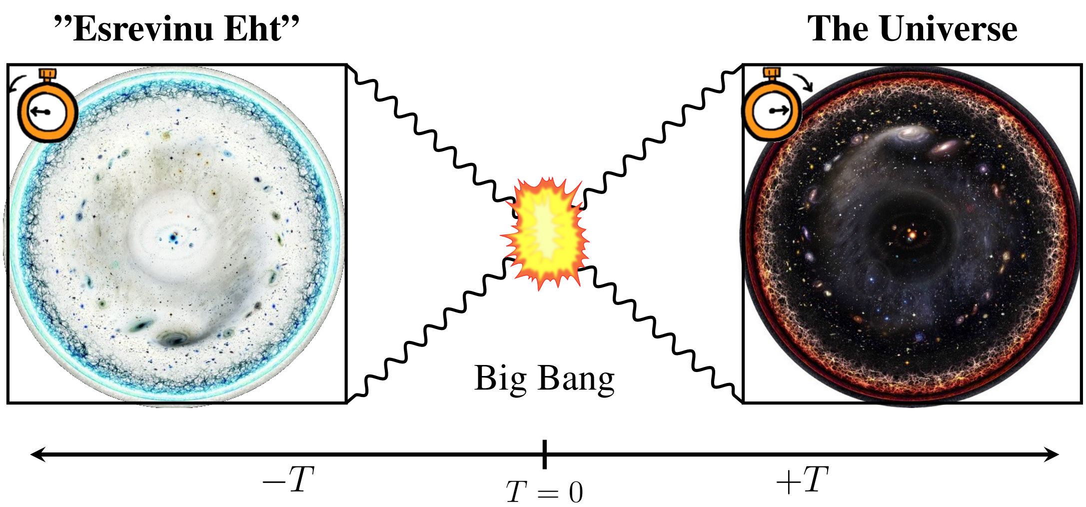

Figure 8: Illustration of the CPT symmetric universe theory. The matter-dominated universe emerges from the Big Bang in the positive direction of time, whereas an anti-matter dominated universe runs in the negative direction of time. At all times, both are exact CPT copies of each other.