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Broken symmetries in particle physics

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Abstract. Symmetries in physics have a special role since they govern the dynamic of physical processes. In elementary particle physics symmetries like parity and charge conjugation, and their breaking have profound consequences, for example, on the matter-antimatter imbalance in our Universe.

1. Introduction

Over the centuries the concept of symmetry has permeated the arts and been related to the idea of beauty. Greek and Roman cornices often represented geometrical and symmetric patterns. The “Vitruvian Man” by Leonardo Da Vinci (c. 1490, now at Gallerie dell'Accademia in Venice) illustrates the ideal proportions of the human body in the symmetric context as inscribed in a circle and in a square. Symmetries and even more broken symmetries are at the heart of physics and in particular of particle physics. The Standard Model of particle physics, the theory describing the fundamental building blocks of matter and their interactions, stipulates that there is a clear underlying structure that pervades the world of elementary particles, starting from the fact that quarks and leptons are grouped into three generations. Figure 1 illustrates this point in two visual layouts of the Standard Model. Beyond the visual representation there are profound connections between symmetries and particle physics. In the following this paper will restrict itself to discrete symmetries and their role in modern particle physics.

2. Discrete symmetries

There are several examples of how discrete symmetries set the scene in particle physics. The paper firstly considers permutation symmetry introduced by Werner Heisenberg in 1926 in relation to identical electrons of an atomic system being indistinguishable. The permutation symmetry is the foundation of quantum statistics: Bose-Einstein and Fermi-Dirac statistics governing the statistical behaviour of indistinguishable quantum particles, e.g. bosons and fermions. Quantum statistics establishes that there are two possible ways in which a collection of non-interacting indistinguishable particles may occupy a set of available discrete energy states at equilibrium: either particles are limited to single occupancy of the same state (fermions) or they are not (bosons). Macroscopic consequences are the structure of atomic levels related to fermions and the phenomenon of superconductivity related to bosons.

Before moving to the second example, it is necessary to introduce angular momentum. An object rotating around a point has an angular momentum that depends on the distance from the centre of rotation and on the velocity of rotation. In the case of minimal or absent friction angular momentum is conserved: an ice skater doing pirouettes will experience different velocities if their arms are contracted or extended. Elementary particles are observed to possess an angular momentum that cannot be accounted for just by angular orbital momentum, i.e. they possess a quantum mechanical, intrinsic angular momentum called spin. Particles behave as if they are spinning about an axis. The allowed spin values are multiples of a base quantity. Wolfgang Pauli proved the spin-statistic theorem: fermions have half-integer spin and bosons have integer spin. Particles are known as fermions if their spin value is a half-integer multiple of the base quantity and are known as bosons if it is an integer multiple. Quarks, leptons, baryons and antibaryons are all fermions. Force carriers and mesons are all bosons. Indeed ordinary matter is made of fermions held together by bosons [1] (see figure 1 for the elementary particles of the Standard Model).

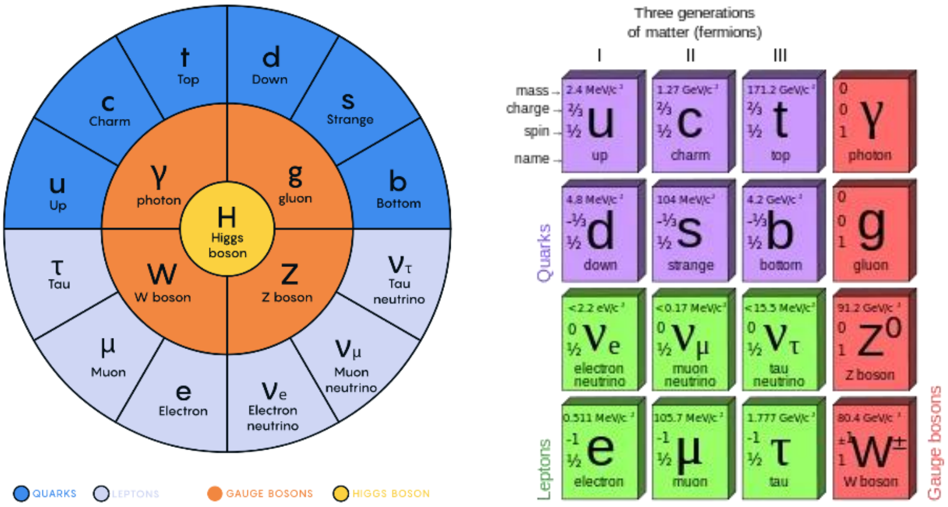

Figure 1. Illustration of the elementary particles in the Standard Model (Image credit: Wikipedia and Quant Magazine).

Parity plays a very special role in particle physics. Mathematically parity is the reflection against the origin of the chosen coordinates system. Physically this is equivalent to taking the mirror image and rotating it by 180 degrees. We as humans are naturally acquainted with parity as space reflection (like in a mirror). At the human scale the structure of matter is dominated by the electromagnetic force that is known to respect parity; in fact the laws governing gravity, electromagnetism and the strong interactions all respect parity. Parity in a quantum context does indeed give insights into allowed and forbidden atomic transitions and spectroscopy.

While parity conservation is ubiquitous it is not always respected: most notably it is now known that weak interactions violate parity and in the 1950s the scientific world got a systemic shock. Firstly, Tsung-Dao Lee and Chen-Ning Yang pointed out that beta decays had not yet been tested for parity conservation; then Chien-Shiung Wu performed a historic experiment using beta decays of ^{60}Co [2] to investigate. If parity were conserved an equal rate for producing electrons in directions along and opposite to the nuclear spin would have been expected. Instead the unexpected result was that one possible experimental outcome is much more likely than its mirror image (see figure 2).

Fundamental weak interactions acting in beta decays couple only to ‘left-handed states’, i.e. particles with the projection of their spin anti-parallel to their momentum. This is a 100% violation of the parity symmetry. The existence of parity violation has implications on the philosophical debate concerning chiral or handed objects and the nature of space. A description of a left hand and one of a right hand will not differ as long as no reference is made to anything beyond the hand itself. Nonetheless left and right hands do have differences, for example, a left-handed glove will not fit on a right hand. Right and left hands are mirror images of themselves but cannot be made to coincide by any rigid motion. The question is therefore if the difference between left and right handedness lies in their relation to absolute space or simply in their relation to each other. The dilemma cannot be resolved on the basis of parity alone.

A further discrete symmetry of note is the so-called charge conjugation. The charge conjugation operation replaces a particle with its antiparticle (and vice versa). The name arises because a given particle and its antiparticle generally carry opposite electric charge. Several experiments after the historic experiment by Wu showed that symmetry under charge-conjugation (C) was also maximally violated so that parity (P) violation was compensated by C violation. Since the combined operation of charge conjugation and parity (CP) was still a good symmetry the need for an absolute distinction between left-handed and right-handed co-ordinate systems was avoided. But another systemic shock was about to happen in the scientific world.

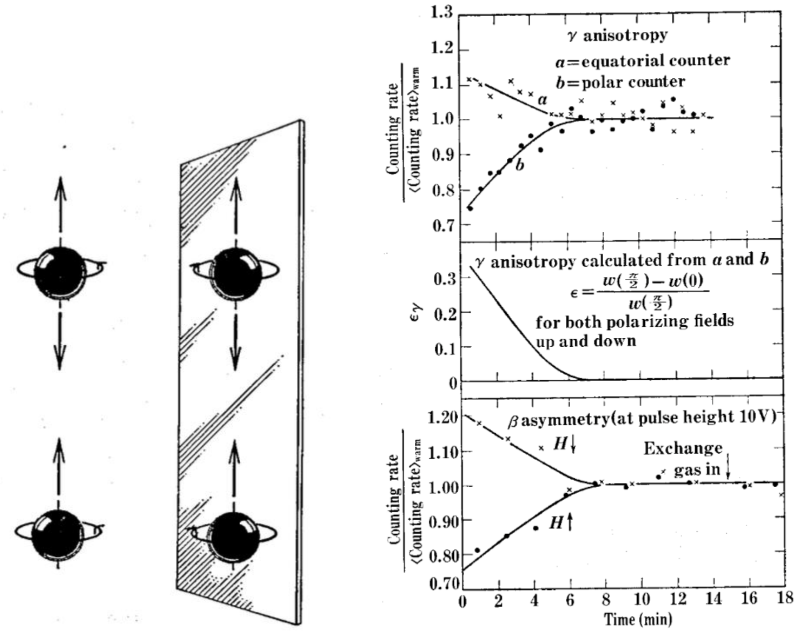

Figure 2. Left: The mirror reflection of a spinning ball. The image and the real object could not be distinguished because the top right one looks just like the real ball turned upside down. Reflection can be detected if there is a preferred direction. Right: Results of β-asymmetry and γ-anisotropy from the polarised ^{60}Co experiment. The two effects coincide exactly at the same time and the measured asymmetry indicates that the emission of electrons is preferred in the direction opposite to that of the nuclear spin [3].

3. CP violation

The existence of positrons with the same mass but opposite electric change to electrons was first predicted and then found experimentally. The formulation of the Dirac equation that regulates the dynamics of fermion, implied the existence of antimatter which was discovered later in 1933 in interactions of a particle beam with the hydrogen filling a bubble chamber.

Indeed every fundamental matter particle has its antiparticle with the same mass, opposite charge and same lifetime. At particle accelerators it is observed that the collision of a particle and its antiparticle produces energy in the form of radiation. Equivalently particle experiments show that equal amounts of matter and anti-matter are produced when energy is converted into matter. Inevitably for every quark or lepton created, an antiquark or antilepton is also created. It therefore must be assumed that equal amounts of matter and antimatter should have been created during the Big Bang.

However, we live in a Universe made from matter with extremely little antimatter around that is produced in particle collisions, natural (cosmic ray collisions) or man-made (accelerator collisions). Something must have therefore happened shortly after the Big Bang that caused an initial imbalance of matter over antimatter, i.e. immediately after the Big Bang matter and antimatter were no longer exactly equal in numbers. The annihilation then happened where all the antimatter and all but a tiny part of the matter were transformed into radiation, and the remaining tiny part of matter makes up the whole matter of the Universe. The origin of the initial matter-antimatter imbalance is still largely mysterious but violation of CP is one of the necessary conditions for the matter-antimatter imbalance to happen. Before looking at the discovery of CP violation let us take a step back.

In the Standard Model up to now transitions between composite particles made of quarks are the only known phenomena where CP violation clearly manifests itself. Single free quarks are never observed as quarks are always confined in bound states called hadrons. Macroscopically hadrons behave as point-like composite particles. Baryons and mesons are types of hadrons. In particular mesons are hadrons consisting of a quark and an antiquark. Pions are the lightest mesons containing only up and down quarks or antiquarks.

Discovered in cosmic rays in the 1940s, neutral kaons are mesons containing one strange quark ($\bar{K}^0$ or antistrange quark in K^0) and one antidown quark (or down quark) with resulting zero net charge. Strange quarks are assigned a "strangeness" quantum number of -1 while antistrange quarks have a strangeness of +1. Strangeness is conserved in strong interactions meaning that in a strong-force-mediated process if an initial state has zero net strangeness, the final state also has zero net strangeness, i.e. a strange quark is produced in association with an antistrange quark. If neutral kaons are being considered, a K^0 is produced together with a $\bar{K}^0$. Kaons undergo weak-force mediated decays commonly to pions. However, the kaon states of definite mass and lifetime, i.e. the measured quantities experimentally, are somehow different than those at production: labelled K1 and K2 they are a quantum admixture of the two particles K^0 and $\bar{K}^0$ (called "mixing"), and are even and odd respectively under the CP transformation. Under the assumption of CP conservation in the decays the K2 state is forbidden to decay to two pions. This gives it a much longer lifetime than the K1 and this is verified experimentally with the two identified particles called K-short (K_S) and K-long (K_L). The K_L would instead decay into three pions.

This time no-one thought that CP violation could be violated. Because K^0 and $\bar{K}^0$ have different interactions with matter, if an initially pure K_L beam enters a material the K^0 component will interact more, forming a different admixture of K^0 and $\bar{K}^0$ at the exit of the material, which means that a component of K_S appears or in other words is *regenerated* in the beam. Regeneration is not an effect of CP violation but it is a phenomenon peculiar to the kaon system. An experiment was approved for two hundred hours of run-time and setup at Brookhaven in 1963 with the main aim of studying regeneration. A beam of K_S and K_L was produced, and kaon decays were identified about 17 m downstream (see figure 3); there one would expect only K_L to survive, hence to see only three pion decays. Finding a “new upper limit” for K2 decaying to two pions was a secondary consideration listed under “other results to be obtained” and about half of the run-time was devoted to the “CP invariance run”. To the surprise of the scientific community Val Fitch, James Cronin and René Turlay's experiment saw evidence in 1964 of K_L decays into two pions, that is, certain evidence of the existence of CP violation [4].

To further understand the origin of CP violation physicists needed to make a subtle comparison between K_S and K_L decays in pairs of neutral and charged kaons. In 1987 the NA31 experiment at CERN provided the first evidence of direct CP violation, that is, it happens in the decay of the neutral mesons, not only in the mixing between neutral kaons. When the competing experiment at Fermilab called E731 did not find significant evidence it became clear that more precision was needed to confirm the original observation [6]-[8]. A second generation experiment called NA48 also located at CERN accepted a much higher primary-proton intensity and therefore was able to measure the four decay modes concurrently thanks to the deflection of a tiny fraction of the primary proton beam into a downstream target. Fermilab also had a follow-up experiment called KTeV. Both KTeV and NA48 confirmed NA31's results, firmly establishing direct CP violation and its complex nature [9]-[12]. Since then CP violation has been observed and then precisely measured in the beauty quark sector by the LHCb experiment at CERN. Nonetheless the amount of CP violation in the Standard Model remains small and it is a mystery as to why the observed matter-antimatter imbalance is so large in the Universe.

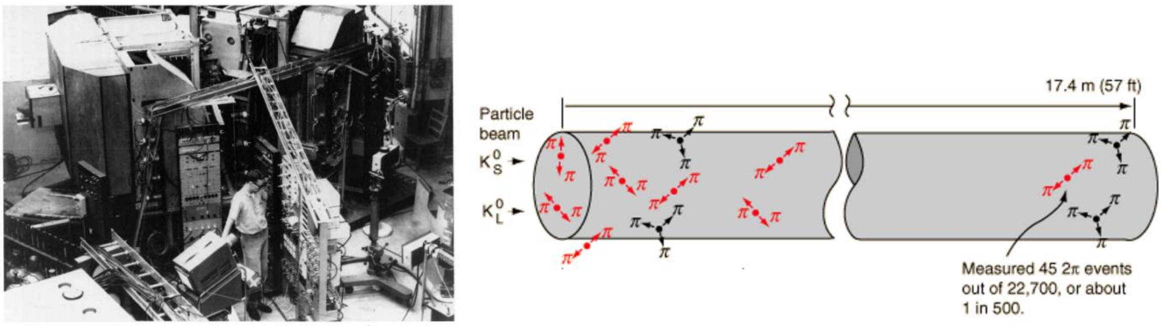

Figure 3. Left: The only existing photograph of the apparatus. Right: Illustration of the experimental situation [5]

This time there is no escape; the discovery and understanding of CP violation leads to the conclusion that the microscopic laws of physics allow an absolute distinction between left- and right-handed co-ordinate systems between particles and antiparticles. It must be concluded that the Universe is chiral and without CP violation would just be full of photons and we would not be here to discuss this topic.

4. Symmetry breaking

Whenever a symmetry is not satisfied there is a situation of a symmetry breaking. There are plenty of examples of symmetries and broken symmetries in Nature. While the human body is roughly left-right symmetric no-one is perfectly so and an engineered picture of a human face that is perfectly symmetric does in fact feel unreal. The point of broken symmetries has been widely debated for centuries. A famous example is given by the medieval French philosopher Jean Buridan, who debated the paradox of a donkey that finds itself between two identical carrots, each side at the same distance; the donkey is unable to decide which carrot to eat first and so dies of starvation. This theoretical situation is easily resolved in reality: a real donkey would choose randomly the first carrot and eat both instead of dying, demonstrating that symmetry is broken in Nature.

In quantum theory there are two possible ways of a symmetry breaking. If it is explicitly broken, the symmetry-breaking terms are introduced into the theory by hand on the basis of experimental results like P and CP. If the symmetry is spontaneously broken, solutions to a certain problem exist which are not invariant under the action of this symmetry without any explicit asymmetric input.

To illustrate the spontaneous symmetry breaking idea, let us consider a linear vertical stick that is somehow flexible. The physical description of the stick is obviously invariant for all rotations around its vertical axis. Now let us compress the stick equally at both ends. As long as the applied force is mild enough the stick does not bend and the equilibrium configuration, i.e. the lowest energy state, is invariant under rotation symmetry. When the force reaches a critical value the symmetric equilibrium configuration becomes unstable and an infinite number of equivalent lowest energy stable states appear, which are no longer rotationally symmetric but are related to each other by a rotation. The actual breaking of the symmetry will then naturally occur by any external cause and the stick will bend, taking one of the infinite possible stable asymmetric equilibrium configurations, now the lowest energy state or ground state. There are then many different "possible worlds" in which the stick falls in one particular ground state and all worlds are equivalent. The original complete invariance under all rotations around the vertical axis is present in the underlying physical theory but not in the actual realisation. There might be symmetries in Nature that are not manifest to us because the physical world we live in is built on a vacuum state that is not invariant under them.

The phenomenon is ubiquitous in condensed matter physics, for example, in crystallisation. A circular bowl of water looks the same from all directions and it has rotational symmetry. When it freezes, however, the ice crystals line up in particular directions, breaking the symmetry. Such a mechanism is also at work in the so-called quantum gauge theories such as the Standard Model Higgs boson theory. In this case the symmetry breaking is induced by another field, the Higgs field which has the peculiar property that it wants to be non-zero. Most fields oscillate about a zero average like a marble rolling in a circular bowl. In the case of the Higgs field the bowl has a hump in the middle like a sombrero and the would-be marble oscillates around a point in the valley, breaking the symmetry (see figure 4, left). This non-zero mean value also gives masses to the particles with which the field interacts, including the three weak gauge bosons. The field oscillations constitute another particle, the Higgs boson with the unique feature among the known elementary particles of having no spin. A consequence of this is that without the existence of the Higgs boson elementary particles would not have mass, which has profound implications. For example, the electron mass is related to the stability of the atom, i.e. massless particles would not allow stable atoms; since atoms are the backbone of any large-scale structure massless particles would produce a structureless Universe.

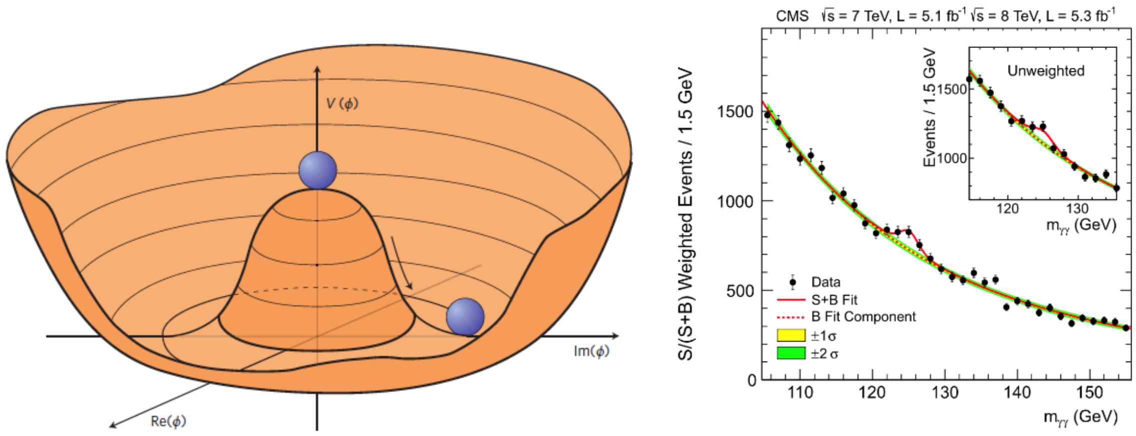

Figure 4. Left: Illustration of the Higgs potential [15] (Image credit: CERN). Right: Di-photon invariant mass distribution for the CMS data of 2011 and 2012; black points with error bars [14] (Image credit: CERN-CMS).

In July 2012 the ATLAS and CMS experiment teams at the CERN Large Hadron Collider announced the discovery of a new particle (see figure 4, right) consistent with a Higgs boson [13], [14]. The discovery was front page news around the world, became a top trend on Twitter and attracted the 2014 Nobel Prize in Physics. Since then many more measurements at increased statistical power have been made, contributing to further understanding of the Higgs boson and the way it interacts with the other elementary particles. It is still a puzzle why the Higgs boson should be light as interactions between it and Standard Model particles would tend to make it very heavy. Additional non-Standard Model particles could cancel out the contributions to Higgs mass from their Standard Model partners, making a light Higgs boson possible. Supersymmetry is a possible theory that would also link the two different classes of particles known as fermions and bosons since each of the particles in the Standard Model would have a partner with a spin that differs by half of a unit such that bosons would be accompanied by fermions and vice versa. Nonetheless at present there is no experimental evidence for supersymmetry.

5. Conclusion

In this short paper a number of discrete symmetries have been defined that are important in physics and their effects have been described. Then the violation of such symmetries was introduced with particular attention to parity and CP, and their discovery was described. Considering the profound implications that broken parity, CP and spontaneous symmetry breaking have it can be concluded that broken symmetries are essential for the existence of our world the way it is.

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