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# Mirror symmetry and fundamental interactions

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Our modern representation of elementary processes considers that all physical phenomena result from the interplay of four fundamental interactions: the gravitational attraction, the electromagnetic force, the strong interaction and the weak interaction. Formally, the quantum mechanical description of elementary processes introduces the concept of discrete symmetry, illustrated for instance by space and time inversions. Discrete symmetries play a central role in the elaboration of theories and models, and have profound consequences in the predictions of these theories. For nearly 50 years, it has been observed that, of the four fundamental interactions, only the weak interaction violates mirror symmetry, and all observations so far indicate that it does so in a so-called maximal way. Despite overwhelming evidence of mirror-symmetry breaking, the search for a possibly underlying left–right symmetry has been pursued for many years by dedicated experiments. In this paper we review the context of mirror symmetry breaking in the weak interaction, we describe its interpretation in the framework of the standard model of particle physics and describe current efforts to identify the restoration of the left–right symmetry.

## Introduction

The laws of classical physics have always shown complete symmetry between the left and the right. The distinctions between a physical phenomenon and its mirror image in classical physics arise solely from the initial conditions, which are accidental, and not from a fundamental asymmetry in the laws. The principle of mirror symmetry has been used in classical physics precisely to exclude theories or models enabling the distinction between left and right, but it has otherwise no great practical importance. The question of whether elementary processes in physics could enable one to distinguish left from right was examined by Lee and

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Yang in 1956. They suggested that the question about the conservation of mirror symmetry, or 'parity', should be addressed empirically, which led to the discovery of parity violation in the weak interactions. In other words, the breaking of the parity symmetry in the weak interactions provides a mean of distinguishing left from right in physical processes.

Parity violation has been incorporated as a fundamental assumption of the modern unified theory which describes physical processes at the most elementary level. The violation of the symmetry is furthermore assumed to be maximal and all observations performed so far are consistent with the predictions of the theory. Many attractive theoretical scenarios consider that the breaking of parity symmetry observed at the energies available in laboratory experiments is only a manifestation of a deeper left–right symmetry, which should hold at much higher energies, like those that prevailed at an early phase of the Universe. In the past two decades several dedicated experiments have been performed to search for indications of an underlying left–right symmetry, but despite the strong improvements in the experimental sensitivities to mirror-symmetry breaking effects, no signature of a restoration of the symmetry has been observed so far.

In this paper we review the status of the mirror symmetry violation in the weak interactions, and describe recent experimental attempts at looking for its restoration.

## Fundamental interactions

The complexity and diversity of phenomena around us is ascribed to the interplay between four fundamental interactions: the gravitational attraction, the electromagnetic force, the strong interaction and the weak interaction. Most phenomena observed at the macroscopic scale are due to the gravitational and electromagnetic interactions, which were historically the first to be described formally in great detail. This does not mean that the strong and the weak interactions are only of importance at the microscopic scale. For instance, the shining of the sun and the speed at which the burning of the nuclear fuel takes place in stars are due to reactions driven by the strong and the weak interactions.

The strengths of these interactions relative to the strong interaction are presented in Table 1. The gravitational interaction has such a small strength that it is generally neglected from the description of processes at the microscopic scale. The third column in Table 1 gives examples of bound systems dominated by the corresponding interaction. In contrast to the other three interactions, the weak interaction has no known bound system associated with it. Incidentally it is often introduced as being 'the one responsible for the decay of some unstable particles'.

Fundamental interactions are described by the appropriate *fields of force*. The quanta of these fields are particles called the *fundamental bosons.* These are listed

**Table 1.** The four fundamental interactions. The second column gives the typical strength of the interaction relative to the strong interaction, the second provides an example of a bound system and the last lists the corresponding force carrier.

| Interaction | Strength | Bound System | Force Carrier |
|---|---|---|---|
| Gravity | $10^{-38}$ | solar system | $G$, graviton |
| Electromagnetism | $10^{-2}$ | atoms | $\gamma$, photon |
| Strong | 1 | nuclei, nucleons | $g_\lambda$, gluons |
| Weak | $10^{-6}$ | – | $W\pm^{0}$, weak bosons |

in the last column of Table 1. The quantum of the electromagnetic field is the photon, $y$; the quanta of the strong field are eight gluons, $g_\lambda$; and the quanta of the weak interaction are the three bosons, $W^+$, and $Z^0$. All fundamental bosons except the graviton have been observed experimentally.

The range of an interaction can be related to the mass of the force carrier. For the gravitational and electromagnetic interactions the range is infinite as the corresponding bosons have zero masses. Considering that the mass of the charged weak bosons, $W^\pm$, is

$$m_W = 80.4 \text{ GeV/c}^2 \tag{1}$$

an estimate of the range of the weak interaction can be obtained using the fundamental physical constants and generating a quantity having the dimension of length

$$r_w = \hbar/m_w c \approx 2.5 \times 10^{-3} \text{ fm} \tag{2}$$

where $\hbar$ is Planck's constant and $c$ is the speed of light in vacuum. It is seen that $r_w$ is a tiny fraction of the size of a nucleon, which has a radius of about 1 fm $(=10^{-15}$ m).

## Matter particles

At the most elementary level, the constituents of matter are the *leptons* and the *quarks* (Figure 1). These are our modern 'atoms' in the sense of indivisible entities and, as such, they are considered as point-like objects. Leptons and quarks are *fermions* as they carry half-integer spin and obey the so-called Fermi–Dirac statistics for the description of systems with several particles.

There are six quarks (up, down, charm, strange, top and bottom) and six leptons (electron, muon, tau and their corresponding neutrinos). To each fermion one associates an antiparticle, which has the same mass and lifetime but which has

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**Figure 1.** The fundamental fermions

otherwise opposite charges (electromagnetic charge, weak charge, etc). Antiparticles can be considered as mirror particles relative to a transformation that changes all the charges of the particle. The fundamental fermions are grouped in three generations. Each generation is constituted by the particles in the columns of Figure 1. When moving from one generation to the next, from left to right, one finds essentially two heavier replicas of the lightest generation, which includes the *u* and *d* quarks and the electron. It is not known at present what is the role of the particles in the heavier generations. Their discovery provided a firm step to the model based on the six quarks, which describes the structure of all particles interacting by the strong interaction, like ordinary nucleons.

All matter around us is made out of the fermions of the first generation. A proton is made out of two *u* quarks and one *d* quark, $p = uud$, whereas a neutron is made out of one *u* quark and two *d* quarks, $n = udd$. The electric charge of the proton and of the neutron are obtained by assigning fractional electric charges to the quarks, $q_u = 2/3$ and $q_d = -1/3$.

There are other striking differences between quarks and leptons: they are not all sensitive to the same interactions. Quarks interact by the strong, the electromagnetic and electromagnetic and the weak interactions, and the neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) interact only through the weak interaction.

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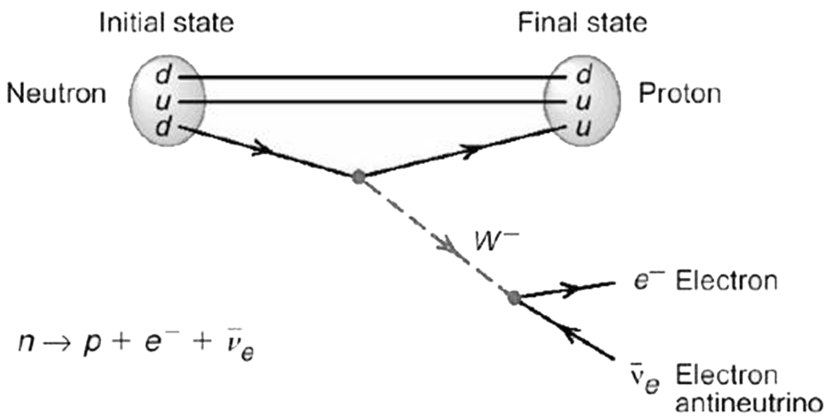


**Figure 2.** The beta decay of the neutron

At the elementary quark–lepton level, the beta decay of the neutron or of nuclei, are described by the exchange of charged weak bosons. Figure 2 shows the decay of a neutron in which a *d* quark is transformed into a *u* quark with the 'emission' of the charged weak boson *W*. This boson, which travels a very short distance, decays then into an electron and an anti-neutrino.

## Symmetries

Symmetry concepts play a central role in physics. The existence of regularities in physical systems, which range from crystal lattices to the structure of baryons, are indications that, although the systems may be complex, one could expect to find simple and unifying explanations of the regularities. This was the primordial role of symmetry considerations in physics, namely to organize data in regular patterns.

At a more fundamental level, the invariance properties of a system under specific symmetry transformations can either be related to the conservation laws of physics or be able to establish the structure of the fundamental interactions. This is the most essential aspect of symmetry as it concerns the basic principles of physics and the interactions themselves and not the structure of a particular system.

Symmetry transformations can be classified in two classes: *continuous* or *discrete* transformations. Continuous transformations are in turn divided into *global* and *local* transformations.

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### *Continuous global transformations*

By definition, a symmetry transformation is said to be continuous if the set of parameters, which are necessary to describe the transformation, range over a continuous set of values. Examples of continuous transformations are the translation in space, the rotation around a given axis, and the translation in time.

For a particle of mass $m$ moving in a one-dimensional space, its classical motion is governed by Newton's equation

$$m\ddot{x} = F \tag{3}$$

If the interaction force, $F$, derives from an energy potential $U(x)$, that is $F = -\mathrm{d}U/\mathrm{d}x$, and if the potential is constant, i.e. independent of $x$, then clearly $m\ddot{x} = 0$. Integration gives $m\dot{x} = C$, where $C$ is a constant. In other words, the invariance of $U(x)$ under the space translation

$$T_a\text{: } x \rightarrow x' = x + a \tag{4}$$

leads to the conservation of the linear momentum $m\dot{x}$. The parameter $a$ in equation (4) can take any real value, hence $T_a$ is a continuous transformation.

In a similar way, one can show that the invariance of a potential under continuous rotations in space leads to the conservation of the angular momentum and the invariance under translations in time leads to the principle of energy conservation. These symmetry transformations are then global because once the transformation of a given point in space has been fixed, then the transformation at all other points in space is also fixed.

In summary, basic principles of physics like the linear momentum conservation, angular momentum conservation and energy conservation result from the symmetry properties of the interactions under global space and time continuous transformations. These crucial connections between the symmetries of a system and the conservation laws are the consequences of a general theorem, Noether's theorem, which states that: 'If a Lagrangian theory is invariant under a N-parameter continuous transformation (in the sense that the Lagrangian function is invariant) then the theory possesses $N$ conserved quantities'. It is one of the cornerstones of classical physics and, by the correspondence principle, of quantum physics as well.

### *Continuous local transformations*

In quantum mechanics, all the properties of a system can be derived from the wave function associated with that system. The absolute phase of a wave function cannot be measured, and has no practical meaning, as it cancels out in the calculation of the probability distribution. Only relative phases are measurable by some sort of interference experiment. It is therefore possible to change the phase of a wave function in a certain way without leading to any observable effect. Formally a phase transformation of the wave function $\psi(x,t)$ can explicitly be written as

$$\psi(x,t) \rightarrow \psi'(x,t) = e^{i\alpha}\psi(x,t) \tag{5}$$

where $\alpha$ is the parameter (phase) of the transformation. If $\alpha$ is constant, i.e. the same for all points in space-time, then equation (5) expresses the fact that once a phase convention has been made at a given point in space–time, the same convention must be adopted at all other points. This is another example of a global transformation applied here to the field $\psi(x, t)$.

Now, if in turn one requires that $\alpha$ be a function of space and time, $\alpha = \alpha(x, t)$, then one can easily see that such a transformation will not leave invariant any equation of $\psi(x, t)$ containing space or time derivatives. This is in particular the case for the Schrödinger equation or any relativistic wave equation for a *free* particle. To satisfy the demands of the invariance under a local phase transformation it is necessary to modify the equations in some way, which will then no longer describe a free particle. Such modifications will introduce additional terms, which describe the interaction of the particle with external fields and thereby generates the dynamics. This is the so-called *gauge principle* according to which the interactions are dictated by invariance under local phase (or gauge) transformations.

### *Discrete transformations*

Symmetry considerations first entered physics with the study of crystal lattices. The symmetry operations that leave unaffected an arbitrary crystal are reflections through certain planes, inversions with respect to a centre point and rotations around a given axis by angles $2\pi/n$, with $n = 2, 3, 4$ or 6, which are rotations compatible with the periodicity of the crystal lattice. These are examples of discrete transformations.

At the level of processes between leptons and quarks there are three discrete transformations that play a crucial role: the charge conjugation $C$, the parity transformation $P$, and the time reversal $T$. First, in a charge conjugation operation, equation (6), all the particles of a system are replaced by their antiparticles and therefore all charges $q_\alpha$ change sign. This symmetry only holds for truly neutral particles, which do not carry any charge. Next, the parity transformation, equation (7), corresponds to a space inversion relative to a point. In a system of Cartesian coordinates, a point with coordinates $(x, y, z)$ transforms into $(-x, -y, -z)$ under the parity operation. In other words, the position vector $\mathbf{r}$ changes sign under a space inversion. Finally, the time reversal operation, equation (8), corresponds to the inversion of the time variable $t$. Pictorially, the invariance under time reversal

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means that it is impossible to distinguish, with the laws of physics, whether a film with a sequence of events (at the elementary level) is being projected in the direction it was filmed or in the reverse direction.

$$C: \quad q_\alpha \to -q_\alpha \tag{6}$$

$$P: \quad \mathbf{r} \to -\mathbf{r} \tag{7}$$

$$T: \quad t \to -t \tag{8}$$

The theory that describes quantum processes and which is compatible with the principles of special relativity, 'the quantum theory of fields', requires the invariance of the fields and interactions under the combined transformation of the three operations, *CPT*. The main consequences of this *CPT theorem* are: (i) if one of the three symmetries is violated then one of the other two symmetries has also to be violated. For instance, the violation of parity *P,* requires that *C* or *T* be violated; (ii) if the invariance under the combination of two transformations holds then the invariance under the third transformation must also hold. For example the invariance under *CP* implies the invariance under *T* and vice-versa; (iii) empirically, the *CPT* invariance implies that the masses and the lifetimes of a particle be identical to those of its antiparticle. This has been confirmed to very high precision and constitutes the experimental tests of the *CPT* theorem.

## Mirror symmetry and parity

A mirror transformation corresponds to the inversion of the position coordinate, which is perpendicular to the plane of a mirror. If we assume that the mirror is on a plane defined by the coordinates $(x, y)$, then the mirror transformation is:

$$\sigma_z: (x, y, z) \to (x, y, -z) \tag{9}$$

This is not identical to the parity transformation of equation (7), which inverts the sign of all space coordinates. The equivalence is obtained by assuming the invariance under rotations. A rotation, $R_z(\pi)$, by an angle $\pi$ around the $z$-axis changes the signs of the $x$ and $y$ coordinates but leaves unchanged the $z$ coordinate. The parity operation is equivalent to the space inversion $\sigma_z$ followed by the rotation $R_z(\pi)$: $P = R_z(\pi)\sigma_z$.

### *Polar and axial vectors*

The vectors used in the description of physical quantities are defined as *polar* or *axial* vectors, depending on their behaviour under a parity (or mirror) transformation. A polar vector changes sign under parity, equation (10), whereas an axial vector does not, equation (11). Examples of polar vectors are the position

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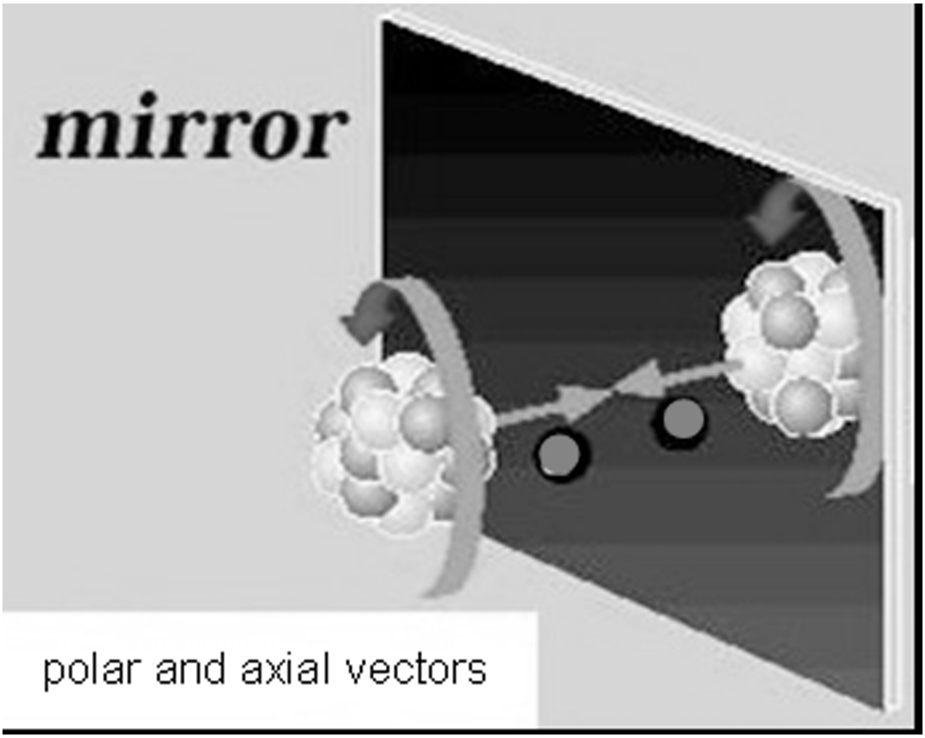


**Figure 3.** The transformation of polar and axial vectors under a mirror symmetry

**r** of a particle in space or its linear momentum **p**. Examples of axial vectors are the angular momentum **J** of a system or the spin **σ** of a particle.

$$P: \quad \mathbf{p} \rightarrow -\mathbf{p} \tag{10}$$

$$P: \quad \mathbf{J} \rightarrow \mathbf{J} \tag{11}$$

Figure 3 shows the effect of the mirror transformation on such vectors. The sense of rotation of a system is defined by the angular momentum, **J**, which is an axial vector. It is seen that the sense of rotation remains the same on the mirror image. In contrast, the direction of motion of a particle, given by the momentum vector **p** is inverted on the mirror image for a particle moving toward the mirror (which is the only relevant direction for the mirror transformation).

It is known that the handedness of a helix is changed by a mirror transformation: a left-handed corkscrew has a mirror image that is right-handed. A helix is defined by both a sense of rotation and a direction of motion. Such quantities, like the helicity, are built by combining a polar and an axial vector in a so-called *pseudo-scalar product*, like $(\mathbf{J}\,.\,\mathbf{p})$ or $(\boldsymbol{\sigma}\,.\,\mathbf{p})$. Looking for the invariance of a system under a mirror transformation consists of searching for the existence of quantities like an helix, formed from the measurable properties of the system.

### *The fall of parity*

Before 1956, it was assumed that parity had to be a fundamental symmetry for physical processes. The image that prevailed at that time can be summarized in the words of Weyl:

> The net result is that in all physics nothing has shown up indicating an intrinsic difference of left and right. Just as all points and all directions in space are equivalent, so are left and right. Position, direction, left and right are *relative* concepts.[1]

In 1956, Lee and Yang examined the question of whether processes driven by the weak interaction would distinguish left from right.[2] This was raised in the context of the so–called $\theta - \tau$ puzzle, in which two particles having the same mass and the same lifetime were considered to be different because their decays sometimes produced states having opposite parity, which was forbidden if parity was to be conserved. Lee and Yang suggested several experiments, involving pseudo-scalar quantities, that would enable them to test empirically whether parity was conserved in the weak interactions or not. The celebrated experiments[3–5] performed in the beta decay of $^{60}$Co, and in the weak decays of pions and muons, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ not only provided the empirical support to the suggestions of Lee and Yang but also showed that parity violation was an universal property of the weak interaction.

The observation of parity violation resides on the fact that, if the $\beta$-decay probability of nuclei contain (pseudo-scalar) terms of the form $A(\mathbf{J} \cdot \mathbf{p})$ or $G(\boldsymbol{\sigma} \cdot \mathbf{p})$, where $\mathbf{J}$ is the nuclear spin, $\boldsymbol{\sigma}$ is the electron spin, and $\mathbf{p}$ is the electron momentum, then if $A \neq 0$ or $G \neq 0$, the probability is not invariant under a parity transformation.

Following the consequences of the *CPT* theorem, the violation of *P* requires the violation of one of the other two discrete symmetries and it was shown by these and other experiments thereafter that the charge conjugation transformation, equation (6), was also violated in these decays.

## Parity and the standard model

The observation of parity violation was soon incorporated in the theory of the weak interaction and is one of the foundations of the modern unified theory of electro-weak interactions, the Standard Model (SM). According to this scheme the weak interaction, as generated by the gauge principle, is mediated only by *left-handed* bosons. For instance, the charged weak boson, $W^-$ in the neutron decay (Figure 2), can only be left-handed, which then produces the handedness of the leptons. In other words, according to the SM, there are no right-handed bosons in nature that could participate to the weak processes.

This is actually not an explanation: the SM shifts the inclusion of parity violation from a phenomenological formulation to a more fundamental level. The question then remains: why are there only left-handed weak bosons? Can we probe the existence of right-handed bosons?

One should notice that all empirical observations performed during the last 50 years are consistent with the assumption of maximal parity violation as incorporated in the SM. The consistency goes far beyond the description of processes dominated by the weak interaction. Parity violating effects have also been observed in processes where the electromagnetic or the strong interactions are dominant.[6] These effects can appear when the transition between an initial and a final state can be mediated by more that one interaction. This is, for instance, the case of atomic transitions, which are dominated by the electromagnetic interaction, mediated by the $\gamma$, and in which the neutral weak boson, $Z^0$, can also take part. The parity violating effects are due to the interference between the electromagnetic and the weak interaction. In addition, the energy domain covered by experiments looking for parity violating signatures ranges from the energy scales available in atomic transitions, of about 10 eV, up the $Z^0$ resonance, i.e. up to the mass-scale of the neutral weak boson, at about 100 GeV/c$^2$. This corresponds to ten orders of magnitude and confirms the universal character of parity violation studied in the fundamental interactions over a very large energy range.

In summary, we have at our disposal a consistent description of all processes where the parity symmetry is violated, although we do not 'understand' the origin of this violation, in the sense that we do not know of mechanisms that produce the appearance of left-handed bosons, as observed in the experiments at laboratory energies.

## Searching for the restoration of the broken symmetry

There are no theoretical obstacles to considering theories that verify all the fundamental symmetry principles of physics but which incorporate right-handed weak bosons along with the left-handed ones. Such theories – named generically *left–right models* – were in fact been elaborated soon after the discovery of the *neutral weak currents*, in the mid 1970s. This discovery was an indirect observation of the existence of the $Z^0$ and provided the first strong support for the electro-weak unification.

The left–right models are extensions of the SM based on a larger gauge symmetry, which generate the new bosons and provide a simple and elegant mechanism to restore parity symmetry. In the simplest scenarios, the introduction of a right-handed boson, $W_R$, can give rise to a mixing with the standard left-handed one, $W_L$, of the form

$$W_1 = W_L \cos\zeta - W_R \sin\zeta \tag{12}$$

$$W_2 = W_L \sin\zeta + W_R \cos\zeta \tag{13}$$

generating the states $W_1$ and $W_2$. These states are called *mass eigenstates* and, if $\zeta \neq 0$, they are not necessarily identical to the states $W_L$ and $W_R$ called *weak eigenstates*. It is possible to show that, for processes in which the available energy is much smaller than the mass of the left-handed boson, equation (1), like the $\beta$ decay of nuclei, the decay of the muon and the decays of many other particles – the physical properties which are sensitive to parity violation (the pseudo-scalar quantities) can be described by two additional parameters, the mixing angle $\zeta$ in equations (12) and (13) and the mass ratio

$$\delta = (m_1/m_2)^2 \tag{14}$$

where $m_1$ (respectively $m_2$) is the mass of the charged boson $W_1$ (respectively $W_2$). The SM corresponds to $\zeta = \delta = 0$, which also means that $m_2 \rightarrow \infty$. It is then expected that, if a mirror symmetry restoration takes place it would happen at some larger but finite energy scale, i.e. $m_2 >> m_1$.

There are strong experimental indications that, if there is any mixing in such a scenario it should be very small, $\zeta < 0.002$, hence the ratio given in equation (14) becomes the ratio between the masses of the weak eigenstates, $(m_L/m_R)^2$. The mass, $m_L$, of the left-handed boson is given in equation (1), $m_L = m_W$, so that the sensitivity of an experiment can finally be expressed in terms of the mass scale, $m_R$, which can be reached.

The general principle to search for indications of a restoration of parity is to measure a pseudo-scalar property (or a combination of these) with the highest possible precision and to compare the result with the unambiguous prediction of the property made within the SM. Provided that the underlying assumptions of the analysis are valid, any difference between the measured result and the SM prediction would then be attributed to an effect associated with the left–right symmetry restoration.

### *Examples of recent experiments*

The experiments that established the discovery of parity violation consisted of measurements of *decay asymmetries*, that is, they looked for the presence of a term of the form $A(\mathbf{J} \cdot \mathbf{p})$ in the decay probabilities of nuclei and of the muon. Another observable that has been extensively studied to test the violation of parity in nuclear $\beta$-decay is the longitudinal polarization of the $\beta$-particles. Formally this corresponds to looking for a term of the form $G(\boldsymbol{\sigma} \cdot \mathbf{p})$ in the decay probability,

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whereas empirically it is a measurement of the handedness of the particle. Experiments performed in the 1960s and 1970s used unpolarized nuclei for such tests and were able to show that, over a wide energy range, the results were consistent with the standard model prediction

$$G = \pm v/c \tag{15}$$

where $v$ is the velocity of the electron or positron and the upper (respectively lower) sign applies to positron (respectively electron) decays. In short, electrons from $\beta$-decay were observed to be left-handed and positrons were right-handed. The relative precision reached by these absolute measurements was at the level of about 2%.

These experiments have been followed in the 1980s by a second generation of tests, also with unpolarized nuclei, in which the longitudinal polarizations of $\beta$-particles were compared from two different transitions measured simultaneously. The comparison of polarizations was able to circumvent some limiting instrumental effects inherent in the measuring techniques and increased thereby the sensitivity of the measurements. However, the ratio of polarizations that results from these relative measurements is sensitive to the product $\zeta\delta$ and therefore become insensitive to the mass scale $m_R$ in the limit of no mixing, $\zeta = 0$.

Relative measurements with polarized nuclei could be performed in the 1990s following the developments of the online production of $\beta$ emitters and the improvements in the polarimetry techniques. Attractive candidates for these measurements are nuclei that decay through transitions having a $\beta$-asymmetry parameter $A$ close to unity. The measurements compare the longitudinal polarizations of $\beta$-particles emitted in two opposite directions relative to the nuclear spin, **J** and combine in some way the two types of pseudo-scalar terms discussed above, $A(\mathbf{J} \,.\, \mathbf{p})$ and $G(\boldsymbol{\sigma}\text{-} \,.\, \mathbf{p})$.

Two such measurements have been performed so far,[7–9] one in the decay of $^{107}$In nuclei and the other in the decay of $^{12}$N. Both are positron decays and used the same technique to measure the longitudinal polarization of the positrons. These measurements have reached a relative precision level of $10^{-3}$. The results are again consistent with the SM and can be considered among the most precise tests to date of maximal parity violation in nuclear $\beta$-decay.

## Status

Other dedicated experiments in muon decay and indirect searches in high-energy physics also provide limits on the mass scale of a possible right-handed boson. At present, the sensitivity reached by experiments in nuclear decays corresponds, in the simplest scenario described above, to a mass scale at the level of $m_R > 300$–$350$ GeV/c$^2$, those performed in muon decay are at the level of

$m_R > 400$–$500$ GeV/c$^2$ whereas the indirect searches at higher energies probe the mass range $m_R > 750$–$800$ GeV/c$^2$.

It should however be noticed that the study of different decays and reaction processes is of great interest due to the complementarity of the results when considering other extended left–right models, which include more parameters. The confrontation of results from experiments performed at different energy scales and on different systems could pave the way for a possible left–right symmetry restoration.

## Summary and outlook

We have revisited the context of mirror-symmetry breaking in the weak interaction, along with the present interpretation in the framework of the standard model of particle physics. We stressed that all experiments performed so far, either dedicated or indirect, are consistent with the assumption of maximal parity violation, although we do not have a satisfactory explanation for it. We discussed current experimental efforts to identify possible sources of the left–right symmetry restoration and indicated their level of sensitivity.

Present theories or models that extend the SM do not provide any robust prediction of an energy scale at which the left–right symmetry restoration could, if at all, take place. For a few of years we have known that neutrinos have mass, although we do not know their absolute mass scale except that it has to be below about 1 eV/c$^2$. Some scenarios consider that if the (massive) neutrinos are identical to their anti-particles and if they have some interaction with right-handed bosons then they could be responsible, as virtual particles, of a very rare process called *neutrino-less double $\beta$-decay*. Such a process has never been observed so far but constitutes the focus of a very active field of research.

In any event, it is clear that, as with the discovery of parity violation in the weak interaction, the search for a left–right symmetry restoration remains purely an experimental matter.

## Acknowledgement

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**Oscar Naviliat-Cuncic** held a postdoctoral position at the Institute for Particle Physics of the ETH Zurich and a short fellowship at the Laboratory for Corpuscular Physics in Caen before becoming Professor in the Department of Physics of the University of Caen. His interests focus on the tests of the symmetry properties of the fundamental interactions by means of precision measurements at low energies and on the development of the experimental tools for such measurements. Current research projects include the study of correlations in nuclear $\beta$-decay using ion traps and an improved measurement of the electric dipole moment of the neutron using ultra-cold neutrons.