Symmetry Principles and Conservation Laws in Atomic and Subatomic Physics – 2

P C Deshmukh and J Libby

This article is the second part of our review of the important role that symmetry plays in atomic and subatomic physics. We will concentrate on the discrete symmetries – parity, charge conjugation, and time reversal – that have played a significant part in the development of the 'standard model' of particle physics during the latter part of the 20th century. The importance of experimental tests of these symmetries, in both atomic and particle physics, and their sensitivity to new phenomena is also discussed. To conclude, we describe how 'symmetry breaking' in the standard model leads to the generation of mass via the Higgs mechanism and how the search for evidence of this symmetry violation is one of the principal goals of the Large Hadron Collider, which began operating at CERN, Switzerland in 2009.

(left) P C Deshmukh is a Professor of Physics at IIT Madras. He leads an active research group in the field of atomic and molecular physics and is involved in extensive worldwide research collaborations in both theoretical and experimental investigations in this field. He enjoys teaching both undergraduate and advanced graduate level courses.

(right) Jim Libby is an Associate Professor in the Department of Physics at IIT, Madras. He is an experimental particle physicist specialising in CP violating phenomena.

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1. Discrete Symmetries

Apart from continuous and dynamical symmetries, there are other kinds of symmetries that are of importance in physics. In particular, we have three discrete symmetries of central importance in what is known as the 'standard model' of particle physics. These discrete symmetries are: (i) P (Parity), (ii) C (Charge conjugation, i.e., matter/antimatter) and (iii) T (Time-reversal), often known together as PCT symmetry. In physical reactions of particle physics, these symmetries lead to conservation principles operating either separately or in combination. We shall now discuss these discrete symmetries.

1.1 Parity

Parity is the symmetry we see between an object and its mirror image. It is interesting that in a mirror, we usually see the left go to right, and the right go to left, but we do not see top go to bottom and the bottom to the top. This feature typifies the difference between reflection and rotation. If we represent the transformation of a vector $\vec{r}$ to its image in a mirror placed in the Cartesian yz-plane, then we can express the transformation $\vec{r} = (x, y, z)$ to its image $\vec{r}_{\mathrm{I}} = (x_{\mathrm{I}}, y_{\mathrm{I}}, z_{\mathrm{I}})$ by a matrix equation:

$$\vec{r}_{\mathrm{I}} = \Re \vec{r}\,. \tag{1}$$

Now, in the case of reflection, the determinant of the matrix $\Re$ in the above relation is -1, whereas if one writes a similar relation for the rotation of the vector $\vec{r}$ to a new orientation $\vec{r}_{\mathrm{R}}$, the corresponding matrix of transformation would have for its determinant the value $+1$. The reason left goes to right and right to left, but not the top to the bottom and bottom to the top, in a mirror is that we usually tend to imagine the image to have gone to the opposite side of the mirror through a rotation about the vertical axis. If we imagine the rotation to be about the horizontal axis, we would certainly see the top go to the bottom, the bottom to the top, but not left to right or right to left. *Figure* 1 illustrates this. Of course, the fundamental reason is the intrinsic difference between rotation and reflection, exhibited by the different signs of the determinants of their matrices. The parity transformation is thus very different

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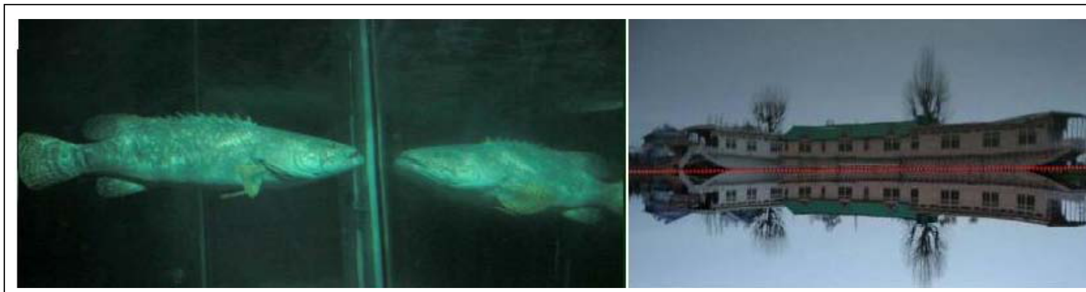

Figure 1. Depending on the plane of reflection, right goes to left and top to bottom; the primary feature discussed in the text is that 'parity' is an operation that is essentially different from 'reflection'.

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from rotation and one may ask, as Alice would (in *Through the Looking Glass*), if the physical laws are the same in the world of images in a mirror. In other words, this question amounts to asking, given the fact that there is a certain degree of invariance when one compares an object with its image in a mirror, whether parity is conserved in nature.

The parity operator Π is a unitary operator which anticommutes with the position operator and also with the operator for linear momentum, since both position and momentum are polar vectors. However the parity operator commutes with the operator for angular momentum which is a pseudovector.

While most of the everyday physical phenomena could take place just as well in essentially the same manner in the image world as in the real world, certain physical phenomena occur differently. The physical phenomena for which parity is violated result from an interaction known as the weak interaction; its most widely-known manifestation is nuclear β decay. The search for parity violation in weak interactions was advocated strongly by Lee and Yang [1], after a careful review of the subject indicated that parity conservation, though often assumed, had not been verified in weak interactions. Acting on the proposals of Lee and Yang, Wu and collaborators clearly observed parity violation in the β decay of polarised nuclei via asymmetries in the distribution of the β-decay electron with respect to the spin of the nucleus (*Figure* 2).

The violation of parity was unexpected. It allowed the first unambiguous definition of left and right in nature.

These and subsequent measurements showed that the weak interaction was maximally parity violation, which meant that it only couples to left-handed chiral states of matter and right-handed chiral states of antimatter; i.e., for a massless fermion this would correspond to the state where the spin is in the opposite direction to its momentum.

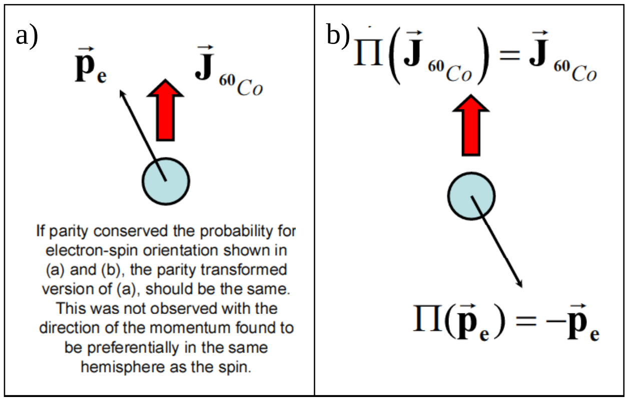

Figure 2. Schematic (a) is of the direction of the β decay electron, characterized by momentum $\vec{p}_e$, with respect to the spin of the ^{60}Co nucleus, $\vec{J}_{^{60}Co}$. Schematic (b) is the same process transformed by the parity operation. Unequal probabilities for these two processes to occur were observed by Wu and collaborators; this was the first experimental evidence for parity violation in nature.

Parity violation is observed in nuclear and subatomic interactions, and through the unification of the weak and electromagnetic interactions, parity is violated in certain atomic processes as well. Atomic transitions are normally governed by the parity selection rule, which then breaks down for those transitions in which parity is not conserved. The electroweak unification achieved in the Glashow–Weinberg–Salam model triggered the search in the 1970s for parity nonconservation (PNC) in atomic processes [2].

The gauge bosons $W^{\pm}$ have a charge of $+1$ and -1 unit, but the Z^0 boson of the standard model is neutral. The latter can mediate an interaction between atomic electrons and the nucleus. The nuclear weak charge QW of the standard model plays the same role with regard to Z^0 that the 'usual' electric charge plays with regard to the Coulomb interaction. PNC effect in atomic cesium yields the value of $QW(^{133}\mathrm{Cs}) \approx -72.90$, not far from the value of $QW(^{133}\mathrm{Cs}) \approx -73.09$ obtained from high-energy experiments extrapolated to atomic scale [3]. The Z-boson has a very large mass and the weak-interaction is 'contact' type. It includes a parity-even part and a parity-odd (PNC) part. While the parity-even part leads to a correction to isotope shift and to hyperfine structure, the PNC part leads to the 'pseudo-scalar' correlations in atomic processes.

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The usual radiative transitions in atomic processes are governed by parity-conserving selection rules imposed by the electromagnetic Hamiltonian. However, once the Hamiltonian is modified to include the electroweak interaction, it does not commute with the parity operator and provides for non-zero probability for parity-violating atomic transitions. The two sources of parity nonconservation (PNC) in atoms are: (1) the electron-nucleus weak interaction and (2) the interaction (sometimes called as PNC hyperfine interaction) of electrons with the nuclear anapole moment. The anapole moment was predicted by Vaks and Zeldovich [4] soon after Lee and Yang's proposal that weak interactions violate parity. The anapole moment is a new electromagnetic moment that can be possessed by an elementary particle (as well as composite systems like the nucleon or nucleus) and this would correspond to a PNC coupling to a virtual photon. The anapole moment can be seen to result from a careful consideration of the magnetic vector potential at a field point after taking into account the constraints of current conservation and the boundedness of the current density.

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A significantly large value of the anapole moment of the nucleon has been estimated in the case of cesium, augmented by collective nuclear effects. Recently, Dunford and Holt [5] recommended parity experiments on atomic hydrogen and deuterium using UV radiation from free electron laser (FEL) to probe new physics beyond the standard model. The Dunford–Holt proposal is based on the consideration that if an isolated hydrogen atom existed in an excited state that is a mix of states $2s_{\frac{1}{2}}$ and $2p_{\frac{1}{2}}$ which have opposite parity, then parity would be violated if the electromagnetic interactions alone were to exist. These two energy states are very nearly degenerate and thus very sensitive to the electroweak interaction which would mix them. More recently, atomic parity violation has been observed in the $6s^2\ {}^1S_0 \rightarrow 5d6s\ {}^3D_1$

408 nm forbidden transition of ytterbium [6]. In this work, the transition that violates parity was found to be two orders of magnitude stronger than that found in atomic cesium. Atomic physics experiments provide a low-energy test of the standard model and also provide relatively low-cost tools to explore physics beyond it.

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1.2 Charge Conjugation and CP Symmetries

The discrete symmetry of charge conjugation (C) converts all particles into their corresponding antiparticles. For example, C operation transforms an electron into a positron. The chirality of the state is preserved under charge conjugation. For example, a left-handed neutrino becomes a left-handed antineutrino; the latter does not interact weakly and shows that C, as well as P, are maximally violated in weak interactions. However, the combined operation CP, on a process mediated by the weak interaction was anticipated to be invariant because, for example, a left-handed neutrino is transformed into a right-handed antineutrino. However, violation of CP is essential to describe the observed state of the universe as being matter dominated. Only differences in behaviour between matter and antimatter, in other words CP violation, can produce such an asymmetry. The presence of CP-violation is one of the three conditions for producing baryons (baryogenesis) in the early universe put forward by the Soviet physicist and dissident Sakharov (1921–1989). He had been inspired to propose CP-violation as an essential ingredient of baryogenesis by the experiments of Cronin, Fitch and collaborators in 1964 that had clearly shown that CP-violation occurs in the weak decays of hadrons containing a strange quark [7].

The origin of CP-violation in weak hadronic decays took some time to describe. It required the bold hypothesis of Kobayashi and Maskawa in 1973 that there was a third generation of quarks to complement the already discovered up (u), down (d), and strange (s) quarks,

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and that time, postulated charm (c) quark. The addition of a third generation of bottom (b) and top (t) quarks leads to a 3×3 matrix being required to describe the weak couplings between the different quarks, which allow for the change of quark type unlike the strong or electromagnetic interactions. It was Kobayashi and Maskawa's great insight that a 3×3 matrix allowed a complex phase to be introduced, which can describe CP-violation in weak hadronic decays. The postulated third generation was not discovered until Lederman and collaborators observed evidence of the b quark in 1977.

The CP-violating parameters of Kobayashi and Maskawa matrix have now been measured accurately principally in experiments at the Stanford Linear Accelerator Center, US, the High Energy Accelerator Research Organisation (KEK), Japan, and the Fermilab National Accelerator Laboratory, US [8]. This confirmation of the three generation model to describe CP-violation led to the award of the Nobel Prize for Physics to Kobayashi and Maskawa in 2008 [9].

Despite the success of this model of CP-violation in the standard model of particle physics, the rate at which it is observed in weak hadronic decays is insufficient to describe the large matter-antimatter asymmetry observed in universe. Therefore, theories that go beyond the standard model must accommodate new sources of CP-violation to explain the rate of baryogenesis. This means that the further study of CP-violation is extremely important. Therefore, flavour experiments are planned at the Large Hadron Collider (see Section 2) and elsewhere. CP-violation may also occur in the lepton sector now that the non-zero mass of the neutrino has been established [10]; however, an exposition of this exciting topic is beyond the scope of this article.

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1.3 CPT Symmetry

The 'Time Reversal Symmetry' (T) is another discrete symmetry. This has a characteristically different form in quantum mechanics that has no classical analogue. The name *time-reversal* is perhaps inappropriate, because it would make a layman suspect that it is merely the inverse of the 'time evolution', which is not the case. In quantum theory, the operator for 'time evolution' is unitary, but that for time-reversal is antiunitary. The quantum mechanical operator Π for parity anticommutes with the position and the momentum operator, but commutes with the operator for angular momentum. On the other hand, the operator for time-reversal, Θ commutes with the position operator, but anticommutes with both the linear and the angular momentum operators.

In quantum theory, the operator for 'time evolution' is unitary, but that for time-reversal is antiunitary.

An important consequence of these properties is the fact that the response of a wavefunction to time-reversal would include not merely t going to $-t$ in the argument of the wavefunction, but also simultaneous complex conjugation of the wavefunction. This property connects the quantum mechanical solutions of an electron–ion collision problem with those of electron–atom scattering through time-reversal symmetry. The physical content of this connection is depicted in *Figure* 3 which represents the fact that in a photoionization experiment it is the escape channel for the photoelectron which is unique whereas in an electron–ion scattering experiment it is the entrance channel of the projectile electron which is

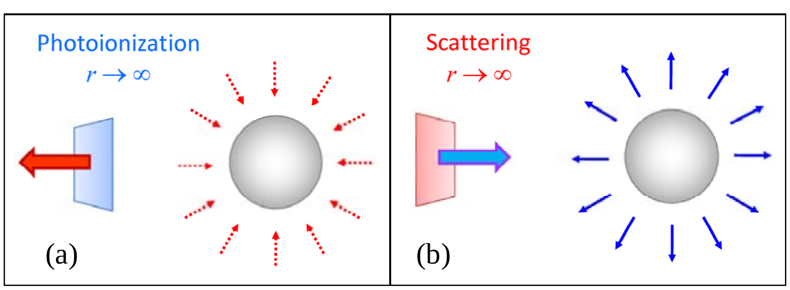

Figure 3. Schematic diagram showing the time-reversal relation between photoionization and scattering processes in atomic physics.

The Lorentz symmetry of the standard model of physics conserves PCT. Violation of T symmetry would require an elementary particle, atom or molecule to possess a permanent electric dipole moment (EDM).

unique. Despite the fact that the ingredients of the electron–ion collision experiment and that of photoionization are completely different, both the processes result in the same final state consisting of an electron and an ion. The initial state, being obviously different, implies that the quantum mechanical solutions of electron–ion scattering and photoionization are related to each other via the time-reversal symmetry [11]. The boundary condition for electron–ion collision and for atomic photoionization are therefore appropriately referred to as 'outgoing wave boundary condition' and 'ingoing wave boundary condition'. The employment of the solutions corresponding to the ingoing wave boundary conditions in atomic photoionization gives appropriate expressions for not just the photoionization transition intensities, but also for the angular distribution and the spin polarization parameters of the photoelectrons.

The Lorentz symmetry of the standard model of physics conserves PCT. The discovery of CP violation in the decay of K mesons [7] therefore made it pertinent to look for the violation of the time-reversal symmetry. Violation of T symmetry would require an elementary particle, atom or molecule to possess a permanent electric dipole moment (EDM), since the only direction with which an electric dipole moment $\vec{d} = | d | \hat{e_s}$ could be defined will have to be along the unit vector $\hat{e_s}$, the direction of the particle's spin. Crudely, this can be schematically shown in *Figure* 4 which shows an angular direction to represent a rotation, and a charge distribution to depict a dipole moment. As t goes to $-t$, the spin reverses, but not the electric dipole moment.

The standard model of particle physics predicts that these dipole moments would be too small to be observable. EDM measurements therefore provide an exciting probe to explore new physics beyond the standard model.

We thus expect from the above equations that the electric dipole moment (EDM) of an elementary particle must be zero, unless both P and T are violated. The standard model of particle physics predicts that these dipole moments would be too small to be observable. EDM measurements therefore provide an exciting probe

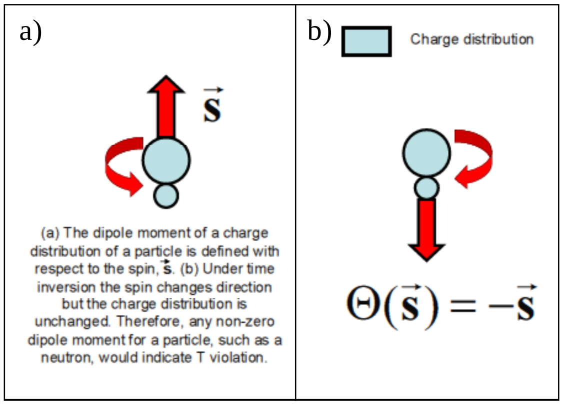

Figure 4. Schematic diagram explaining that the dipole moment of an elementary particle must be zero unless T symmetry is broken. The existence of an EDM also requires that P symmetry is violated.

to explore new physics beyond the standard model. High-precision measurements in agreement with predictions of a robust theoretical formulation would therefore provide a valuable test of the standard model, since limits on EDMs would put conditions on supersymmetric gauge theories [12,13].

2. Spontaneous Symmetry Breaking and the Search for the Higgs Boson

Here we will discuss how symmetry plays an important part in attempts to address another outstanding issue in the standard model of particle physics: How does an elementary particle, such as an electron, attain its mass? The standard model answers this question by assuming that there exists a scalar (spin-less) particle that was predicted in 1964 by Higgs, which is believed to impart a mass to other particles that interact with it. The particle predicted by Higgs is called a Higgs boson, so named after Higgs and Bose (1894–1974).

The standard model of particle physics is a relativistic quantum field theory, which can be expressed in terms of a Lagrangian. The Lagrangian that describes the interactions of a scalar field ϕ is:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 \,, \qquad (2)$$

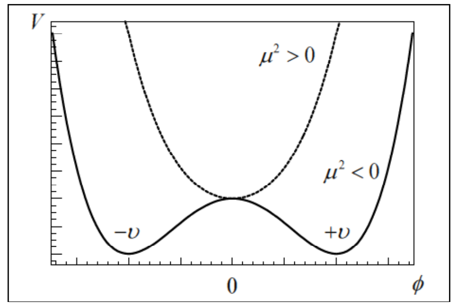

Figure 5. Potential V for a one-dimensional scalar field ϕ for two cases $\mu^2 > 0$, $\mu^2 < 0$, as defined in the text.

where ∂_μ is the covariant derivative and μ is the particle mass and λ is the strength of the coupling of ϕ to itself. The first term on the right-hand side is considered the kinetic energy whereas the other two terms are the potential.

Figure 5 shows the potential as a function of the scalar field ϕ for two cases: $\mu^2 > 0$ and $\mu^2 < 0$. For the case of an imaginary mass ($\mu^2 < 0$) there are two minima at

$$\phi_{\min} = \pm\upsilon = \pm\sqrt{\frac{-\mu^2}{\lambda}} \ . \tag{3}$$

In considering weak interactions we are interested in small perturbations about the minimum energy so we expand the field about *one* of the minima, υ or $-\upsilon$

$$\phi = \upsilon + \sigma(x) \ , \tag{4}$$

where $\sigma(x)$ is the variable value of the field above the constant uniform value of υ. Substituting this expression for ϕ into (2) one gets:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\sigma)^2 - \lambda\upsilon^2\sigma^2 - \left(\lambda\upsilon\sigma^3 + \frac{1}{4}\lambda\sigma^4\right) + \text{constant} \ , \tag{5}$$

The breaking of symmetry provides a hypothesis for the generation of all particle masses – the Higgs mechanism.

where the constant term depends on υ^2 and υ^4 and the third term (in parenthesis) on the right-hand side describes self interactions. The second term corresponds to a mass term with *real* mass

$$m = \sqrt{2\lambda\upsilon^2} = \sqrt{-2\mu^2} \ . \tag{6}$$

The perturbative expansion about one of the two minima has led to a real mass appearing. Since the expansion is made about one or other of the minima, chosen at random, the symmetry of *Figure* 5 is broken. This is the process of *spontaneous symmetry breaking.*

Nambu and Jona-Lasinio first applied spontaneous symmetry breaking as mechanism of mass generation in 1961. In recognition of this work Nambu was awarded a share of the 2008 Nobel Prize [9]. There are many examples of spontaneous symmetry breaking in other areas of physics. For example a bar magnet heated above the Curie temperature has its elementary magnetic domains orientated randomly, leading to zero net field. The Lagrangian describing the field of the magnet would be invariant under rotations. However, on cooling, the domains set in a particular direction, causing an overall field and breaking the rotational symmetry. There are further examples of spontaneous symmetry breaking in the description of superconductivity; these inspired Nambu and Jona-Lasinio's work in particle physics.

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The introduction of such a scalar field interaction and a spontaneous symmetry breaking within the standard model allows the weak force carrying bosons, $W^{\pm}$ and Z^0, to obtain mass as well as all quarks and leptons. In addition, this leads to the physical Higgs boson. The Higgs boson is the only part of the standard model of particle physics that has not been experimentally verified. However, the precise measurements of the properties of the Z^0 and the $W^{\pm}$ by experiments at the Large Electron Positron (LEP) collider, which operated at the European Centre for High Energy Particle Physics (CERN) in Geneva, Switzerland, and of the $W^{\pm}$ and the heaviest quark (the top) at Fermilab, have led to an upper limit on the mass of the Higgs boson of 157 GeV/c^2 with a 95% confidence level. In addition, unsuccessful searches for the production of a standard model Higgs boson at LEP placed a lower limit on the mass of the

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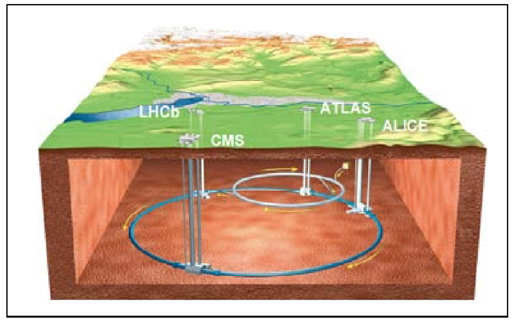

Figure 6. Computer-generated image shows the location of the 27-km LHC tunnel (in blue) on the Swiss–France border. The four main experiments (ALICE, ATLAS, CMS, and LHCb) are located in underground caverns connected to the surface by 50 m to 150 m pits. Part of the pre-acceleration chain is shown in grey.

Higgs boson of 114 GeV/c^2 with a 95% confidence level.

The search for the Higgs boson is one of the principal goals of the largest and the biggest experiment done in the world at the LHC (Large Hadron Collider), a 27 km-long particle accelerator built at CERN near Geneva (*Figure* 6). The LHC stores and collides two beams of protons which are circulating clockwise and counterclockwise about the accelarator [14]. Superconducting dipole magnets generate 8.3 Tesla fields to keep the beams in orbit. The magnets are cooled to 1.9 K, colder than outer space, to achieve these fields. The centre-of-mass collision energy is 14 TeV which is eight times greater than the previous highest energy collider. Such energies have not been produced since approximately 10^{-25} s after the big bang.

The centre-of-mass collision energy is 14~TeV which is eight times greater than the previous highest energy collider. Such energies have not been produced since approximately 10^{-25}s after the big bang.

There are three experiments around the LHC which will record the particles generated in the proton–proton collisions. Two, ATLAS and CMS, are the largest collider particle physics experiments ever built with dimensions of 46 m $\times$ 25 m $\times$ 25 m and 21 m $\times$ 15 m $\times$ 15 m, respectively. ATLAS and CMS will search for collisions that contain Higgs bosons or other exotic phenomena. The third experiment for proton–proton collisions is LHCb, which is dedicated to studying beauty quarks that exhibit CP violation in their decay as discussed in Section 1.2. There is a fourth experiment, ALICE, which will study the strong interaction via events produced when the LHC collides gold nuclei together.

Beams of protons were successfully circulated in both directions about the LHC in September 2008. Unfortunately shortly afterward a fault in one of the 1232 superconducting dipole magnets led to significant damage in one part of the accelerator. Repairs and implementation of additional safeguards has taken just over a year, leading to colliding beams restarting successfully in December 2009. In March 2010 a new world record collision energy of 7 TeV was achieved. The LHC will run at this energy until late 2011, before upgrades to the accelerator will allow collisions at 14 TeV.

Within the next five years the LHC will either confirm the Higgs mechanism or shed light on an alternative model of mass generation.

3. Conclusions

This article (Parts 1 and 2) presents a pedagogical summary of the importance of symmetry principles in describing many aspects of physical theories, in particular those related to atomic, particle and nuclear physics. The continuous symmetries in classical mechanics that lead to conservation of momentum, angular momentum and other quantities such as the Laplace–Runge–Lenz vector, were the starting point. Then discrete symmetries P, C and T were discussed, along with how their violation is embedded within the standard model of particle physics. The particular importance of the combined operation of C and P was emphasised as it maps matter into antimatter. P and T violating phenomena in atomic physics were discussed as the study of these are at the heart of some of the most exciting current atomic physics research. Finally, spontaneous symmetry breaking and the search for this phenomenon in particle physics at the Large Hadron Collider was discussed. We hope the reader is left with a sense of the importance of symmetry and the many areas in which it is significant.

Suggested Reading

[1] Details of Lee and Yang's 1957 Nobel Prize can be found at http:nobelprize.org/nobel_prizes/physics/laureates/1957/index.html

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Address for Correspondence
P C Deshmukh and J Libby
Department of Physics
Indian Institute of Technology
Madras
Chennai 600036.
Email: pcd@physics.iitm.ac.in
libby@physics.iitm.ac.in