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GUEST EDITORIAL

A crisis in fundamental physics

One hundred years of fundamental physics starting with the understanding of the atom, the atomic nucleus and what lies inside have culminated in a theory known as the standard model of high energy physics (SM of HEP). This theory has now been proved to be the correct law of Nature valid down to a length scale of 10^{-17} cm, nine orders of magnitude smaller than the atomic size, i.e. 10^{-8} cm. In this theory, the three fundamental forces of Nature, namely electromagnetic, weak and strong forces are incorporated in the dynamics of Yang–Mills gauge field which is a generalization of Maxwell's electrodynamics. So this theory is the fundamental basis of all phenomena resulting from these three forces. SM is a quantum field theory that combines quantum mechanics and special relativity in a mathematically consistent way.

SM was constructed by theorists more than 40 years ago. Experimenters verified each component of this theory in the next 40 years, except for one component, namely the Higgs boson. This last missing piece was discovered only in 2012 and that was big news. This discovery was made at the Large Hadron Collider (LHC) at CERN, Geneva. Where do we go from here? SM is not the end of physics. There are many things yet to be discovered beyond SM, but the biggest omission in SM is gravity, the gravitational force. Remember SM is a theory of only three fundamental forces. The fourth, gravitational force, which in some sense is the most fundamental force is missing in SM.

It is a deep irony of Nature that the twin revolutions of quantum and relativity that powered the conceptual advances of the 20th century and that underlie all the subsequent scientific developments, have a basic incompatibility between them. The marriage between quantum mechanics and relativity has not been possible. By relativity, here we mean general relativity, since special relativity, has already been combined with quantum mechanics leading to quantum field theory which has been used in constructing SM. Gravity which gets subsumed into the very fabric of space and time in Einstein's general relativity has resisted all attempts at being combined with the quantum world. Hence, quantum gravity has become the most fundamental problem of physics.

The most successful attempt to construct quantum gravity is string theory, but there are also other candidates competing for this honour, such as loop quantum gravity. Actually, string theory offers much more than a quantum theory of gravity. It provides a quantum theory of all the other forces too. In other words, it can incorporate the SM of HEP also, within a unifying framework that includes gravity. Indian physicists have made top-level contributions in string theory which continues to attract many bright students in the country.

In string theory, a point particle is replaced by a one-dimensional object called a string as the fundamental entity. Its length is about 10^{-33} cm, which is the length scale of any theory of quantum gravity, including string theory. The various vibrational modes of the string correspond to the elementary particles. String theory automatically contains quantum gravity and that is its speciality. However, it is bought at a price. It works only if the number of space dimensions is nine and including time it is 10. Where are the extra six dimensions? They are curled up to form space bubbles at distance scales of the same 10^{-33} cm. Both the string and the extra curled-up dimensions will be revealed only when we can access such length scales.

Strings live in a 10-dimensional world having six compact space dimensions in addition to our familiar four-dimensional space–time. We now know that in addition to the one-dimensional strings, string theory automatically contains two-dimensional membranes and branes of higher dimensions too. String theory is the relativistic quantum dynamics of a mind-boggling variety of interacting extended objects (analogues of chairs, tables, cars, etc.) living in a 10-dimensional world. It has rich mathematics and physics. Its richness is continuously being discovered. No wonder, string theory is so difficult. But it can be mastered through mathematics. String theory also requires creation of new mathematics.

To sum up, string theory is the top candidate for a correct theory of quantum gravity, which is the next frontier in fundamental physics after the spectacular success of the SM of HEP.

So has string theory solved the problem of quantum gravity? Perhaps yes, but how do we know? Where is the experimental support for string theory? Remember it took 40 years to verify SM as the correct theory of Nature. It required the construction of particle accelerators of

higher and higher energy ultimately culminating in the construction of the LHC reaching energies in the trillion electron volt (TeV) region. This machine is a behemoth. It is a circular ring of 28 km in circumference and its construction took 20,000 physicists and engineers working for 20 years. In relativistic quantum mechanics there is an inverse relationship between the length scale and the energy required to probe it. Remember that we have descended down to a length scale of 10^{-17} cm. To probe this, we needed the TeV energies of LHC. So, to probe the length scale of quantum gravity (10^{-33} cm), we need 16 orders more energy, i.e. 10^{16} TeV. This is the Planck energy, that is required to experimentally test string theory or any theory of quantum gravity. Most people think this is not possible. This is the crisis in fundamental physics.

If current ideas in cosmology are correct, then the early Universe provides us with a HEP laboratory where particle energies were almost unlimited. So it is believed by many that our theories of quantum gravity can be tested by appealing to events in the early Universe. At the risk of getting a flak from many of my respected colleagues, I would like to strike a note of caution. We know of only one Universe and the events presumably occurred only once, that too quite a long time ago. Modern science owes its existence to the advent of repeatable experiments under controllable conditions, whereas history provides only a single sequence of events. History cannot be a substitute for science.

Galileo decreed 'Laws of Physics are written in the language of Mathematics, but those Laws can be proved or disproved only by Experiments or Direct Observations'. For 400 years, physics has progressed only by following the path opened by Galileo. If we give up this path now, that will be the end of fundamental physics. Then all the theories that we build for quantum gravity will remain as mere metaphysics. What is the way out?

Actually this pessimism is unwarranted. Human ingenuity knows no bounds. The energy barrier will be crossed. Instead of merely scaling up the sizes of the accelerating machines, we must discover new principles of particle acceleration. Either new principles of acceleration have to be discovered, or there will be an end to HEP by about 2040. Actually this conclusion has nothing to do with quantum gravity or Planck energy. Conventional accelerator technology cannot take us above a few orders of magnitude beyond the present TeV energies.

Growth of accelerator energies over the past 80 years has been phenomenal. The energy has been increasing by a factor 10 every 6 years. I interpret this exponential growth as an optimistic sign for the future of fundamental physics. So, if the same growth can be maintained, 16 powers of 10 can be reached in 96 years. It is long, but not infinite. Even SM took 40 years to be experimentally proved. But this growth is possible only if new principles of acceleration and newer technologies are continuously invented. I have been saying all this for the past many years and advocating pursuit of newer accelerator technologies in our country.

What are the new principles of acceleration? I will give one example. In the last 30 years, many ideas on laser-plasma acceleration are being pursued. Using laser excitation of plasma wakefields, electrons have been successfully accelerated to 1 GeV in 1 cm (compared to kilometre-size conventional accelerators to get similar energies). So table-top accelerators are perhaps not far way. Maybe this will lead to breakthroughs that will help us to cross the super-high energy barrier. It is not claimed that laser-plasma accelerator will take us to Planck energy, but it will be an important step.

Our country must enter into this field of laser-plasma acceleration. I have been discussing this matter with the leading laser and plasma physicists in IPR, BARC, TIFR and RRCAT, and they are quite enthusiastic. One may envisage the following plan of action: (1) Set up a National Task Force for planning R&D for the laser-plasma accelerator. (2) Build a National Centre for Laser-Plasma Accelerator.

To succeed in this venture we need all the good will and help from the international scientific community. The International Conference on Ultrahigh Intensity Lasers held in Goa during 12–17 October 2014, revealed the worldwide progress in the field and also showed that India can expect good support from the world if we take up this challenge. So this is the right time to take the plunge.

This megascience project will need the joint support of many scientific wings of the Indian Government. This is an ambitious plan. It will work only if we think big and dream big. We have to develop an appropriate mindset and a collaborative spirit to succeed.

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