Fundamental Physics in the 21st Century

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Abstract: Various aspects of the current crisis in fundamental physics are examined. An important aspect is the cost and difficulty of experiments and observational facilities. Another aspect is the success of the established theories (Quantum Mechanics, General Relativity, Standard Model of particles and fields, Lambda-CDM Model of physical cosmology). Theories predicting new physics require either extraordinary precision or very high densities of energy for the production of predicted particles or very expensive observational facilities. Equally important perhaps, the limited number of academic positions in fundamental physics is forcing young academicians to follow safe avenues of research. Young researchers do not want to invest time and energy researching the foundational problems, to avoid career risks. Beyond these issues it is becoming clear that new perspectives are needed to break through the current state of stagnation in fundamental physics. A few research directions are suggested in this article.

Introduction

The condensed matter physics community is brimming with excitement as the importance of advanced materials is growing in modern society [1]. Research in topological phases of matter, superconductivity, and exotic materials is attracting talented researchers and funding. There is tremendous excitement and funding in the areas of quantum computing and algorithms, quantum sensing and metrology, and quantum communications [2] [3] as well. Fundamental physics - elementary particles and fields, physical cosmology - on the other hand, is in crisis. Let's examine the dimensions of this crisis and possible developments in the 21st century.

Current sentiment in elementary particle physics

A diverse group of about 180 early-career researchers in particle physics provided feedback as part of the recent update of the European strategy for particle physics (ESPP) [4]. This sentence from the executive summary expresses the majority sentiment in the particle physics community: *"When continuing on the current path, the field will likely be unable to attract the brightest minds to particle physics."*

Progress in particle physics takes time. The experimental side of particle physics is very expensive and technically challenging. The theoretical side involves very difficult calculations requiring supercomputers. Esoteric BSM (beyond Standard Model) theories are waiting for confirmation. It seems that it will be decades before we find hints about deeper reality. Discouraged by the slow progress in particle physics, many promising students choose to go into condensed matter physics or quantum computing. But particle physics is still attractive, as it appeals to human curiosity. It is true that there is no direct benefit from particle physics, but any hints about the inner workings of Nature will benefit humanity in the long run.

Society has the right to question the cost of the experimental programs in particle physics. Despite ongoing debates, a consensus is developing among the developed nations to continue this type of research, albeit with reduced budgets. Decision-makers at the national level consider the indirect benefits of particle physics such as technology development.

Elementary particle physics experiments

It has been 9+ years since the announcement of the discovery of the Higgs boson. Since then the amount of work in terms of accelerator/detector development and data analysis has been impressive. Results are rather modest, however [5]. It seems that the next generation of particle colliders known as Higgs factories will be necessary to learn the details of the Higgs field. Experimental verification of the Higgs coupling to 3rd and 2nd generation fermions has been established. Verification of the Higgs coupling to 1st generation fermions (electron, u-quark and d-quark) will be extremely difficult to establish due to overwhelming background noise. The question of whether the Higgs field couples to neutrinos will remain for the foreseeable future.

Experimental particle physics will probably advance in three fronts:

Higgs factories: based on different versions of colliders (circular proton-proton, circular electron-positron, linear electron-positron). Their geographical locations are in Europe, China, Japan. Before the end of this century muon-antimuon colliders could be built as well.

Neutrino experiments: The nerve center of neutrino experiments will be FERMILAB [6].

Precision experiments: Examples are FERMILAB muon g-2 experiment E989 [7] and Harvard's Electron EDM experiment [8].

Standard model of particle physics

The "Standard Model" is the current theory of elementary particles and fields. It includes the matter particles (6 quarks and 6 leptons), the force-carrying particles (gauge bosons), and the Higgs boson. Leptons are the electron, muon, tau and their associated neutrinos. Gauge bosons are the photon (force carrier of electromagnetism), gluon (force carrier of strong-nuclear force), W and Z (force carriers of weak-nuclear force). Quarks and gluons are the constituents of protons and neutrons.

The Standard Model includes the conservation laws of particle interactions [9]. It is important to point out that the conservation laws are not derived from theory. Conservation laws are based on observations repeated millions of times over the past decades.

The Standard Model cannot explain dark matter. There is no gravity in the Standard Model either. Another weakness of the Standard Model is that it has too many free parameters [10].

The most relevant questions of fundamental physics are listed in a section below. The Standard Model has no answers for these fundamental questions. We have to find a better theory of particles and fields.

Standard model of physical cosmology

The Lambda-CDM Model [11] is currently the standard model of physical cosmology. CDM stands for "cold dark matter". Lambda is the cosmological constant. For a historical perspective on the development of the Lambda-CDM Model, reference [12] can be consulted.

The latest values of the observed parameters of the Lambda-CDM Model are found in the reports of the Planck satellite collaboration [13]. Their conclusions:

- The physical universe contains 4.9% normal matter, 26.6% dark matter and 68.5% dark energy.
- The overall spatial curvature of the universe is very close to zero. This means that in the absence of matter, photons travel in a straight line. Caveat: in the presence of matter, photons follow a curved path (gravitational lensing) as explained by the theory of General Relativity.
- The Planck measurements are consistent with the "cosmic inflation" hypothesis, but there is no evidence for primordial gravitational waves originating from the inflationary period.
- The Planck measurements prove that there are only 3 types of neutrinos.
- The Planck collaboration measured the Hubble expansion rate as 67.4 (km/s)/Mpc, which is lower than the number produced by the cosmic distance ladder method: 73 (km/s)/Mpc). This discrepancy is known as the "Hubble tension."

The Lambda-CDM Model has three ingredients: cold dark matter, cosmological constant, and cosmic inflation. The underlying physics of these ingredients is unknown. The cosmic distance ladder method, on the other hand, is less dependent on assumptions. The authors of reference [14] review the proposed solutions to the "Hubble tension." One of the possibilities is dynamic dark energy, which means that the cosmological constant had different values during early epochs. Reference [14] examines other possibilities as well. It may take the rest of the 21st century to learn the physics of dark matter and dark energy.

Planck-scale physics

Progress in fundamental physics requires a good understanding of the most compressed states of matter and the physics of very high energy densities that are created in violent collisions of elementary particles in cosmic events.

Quantum Gravity - physics of the most compressed states of matter - is a big unknown. The law of gravitation as described by the theory of General Relativity and the laws of elementary particles as described by the Standard Model may not be valid in such extreme conditions. As a matter of fact, we may have to abandon the notions of space and time in a theory of Quantum Gravity.

Assuming the notion of space is still valid, the relevant distance in Quantum Gravity is the Planck length which is approximately the size of a black hole, where its Compton wavelength and Schwarzschild radius are the same. The Planck length is approximately 1.6 x 10^{-35} meters. The proton diameter is roughly 100 million trillion times larger than the Planck length.

The Planck length is probably the shortest measurable distance. In order to probe the interaction of elementary particles at distances shorter than the Planck length, we need to create very high energy densities which would inevitably result in the creation of microscopic Black Holes, which then evaporate instantly due to quantum effects. There are many unknowns in all this, but it is clear that the Planck length is very likely to be the shortest measurable distance.

Since we cannot possibly create the conditions of Planck-scale physics in the laboratory, the only hope for progress would be the detection of the signatures of Planck-scale physics. There is hope that these signatures will be seen in the "precision experiments" of elementary particle physics as well as the "precision observations" of physical cosmology.

Fundamental questions

These are the key questions in fundamental physics:

- Are there undiscovered principles of Nature: new symmetries, new physical laws?
- Are there particles and fields not described by the Standard Model of particle physics?
- Do electromagnetic, weak-nuclear, and strong-nuclear forces become unified at the most fundamental level?
- Can we come up with a theory of Quantum Gravity?
- Why are there exactly 3 families (generations, flavors) of fermions?
- How can we explain the mass ratios of elementary particles?
- What is dark matter?
- What is dark energy?
- The Big Bang should have produced equal amounts of matter and anti-matter, yet the anti-matter is gone. What happened?
- Do protons decay? We can split protons in colliders by smashing them against each other, but do protons decay on their own?
- What is the nature of neutrino mass? Can the neutrino mass be explained by the Higgs mechanism?
- What is a particle?
- What is electrical charge?
- Is there a fundamental relationship between charge and spin?

In terms of precision experiments, any measurement indicating the existence of an electric dipole moment in the electron, muon or tau would lead to new physics.

For a wider survey, the "Open Questions in Physics" maintained by John Baez [15] can be consulted.

Unification themes

Most physicists believe that the universe is governed by comprehensible laws. A majority of physicists believe that the natural laws are part of a single theoretical framework. This belief system and the research program towards finding that single unifying framework is known as the unification program.

It is ironic that the goal of having a single theoretical framework – sometimes referred to as the "Theory of Everything" – gave birth to multiple research programs (group-theoretical approaches based on symmetries, String Theory, Hypergraph, primordial qubit network). The idea of unification seems to inspire multiple approaches. Are these simply candidates, in the sense that only one of them will prove to be correct? Or, do these theoretical frameworks all contain elements of truth, reflecting different aspects of Reality? In my opinion, no single theoretical framework can be declared as the truth. We will keep discovering new perspectives. By “perspectives” I mean those conceptual frameworks with strong explanatory and predictive power. Many other conceptual frameworks will be dismissed, but in the end there will be multiple useful “perspectives”.

Unification of theories may not be possible after all…but there is value in this effort. The unification research program reflects the basic human desire to find a simpler theory.

More comments on the unification themes can be found in reference [16].

The role of Data Science in fundamental physics

In the 1990s, FERMILAB’s CDF experiment was processing hundreds of terabytes of data per year. Two decades later, a year of proton-proton collisions at a single CERN LHC experiment generated close to 1 million petabytes of raw data. Imagine how much data will be generated in future Higgs factories. Experimenters record only a fraction of the raw data after applying sophisticated filters to separate interesting collisions from the background noise in the collision debris. Even after filtering, each experiment ends up recording and analyzing petabytes of data. In the last decade, the CERN LHC experiments recorded 280 petabytes of data on tape.

The Sloan Digital Sky Survey produced 70 terabytes of images of stars and galaxies in 2008. The Large Synoptic Survey Telescope (renamed Vera C. Rubin Observatory) will produce more than 100 petabytes of data over ten years, starting in 2023.

Experimenters use ML (Machine Learning) techniques to sift through the torrent of data [17]. The role of Data Science techniques in fundamental physics will grow in the 21st century.

Agency

The concept of “agency” has not been integrated into our physical theories yet. This is a glaring deficiency of the scientific theories. The role of agency in causation is obvious. When I move my hands and grab the coffee mug and drink coffee the cause of these events is me (the agent). No one in his right mind can argue that water molecules mixed with coffee conspired to enter my mouth. It was my mind directing my muscles to grab the coffee mug and drink the coffee. The laws of physics are involved throughout the process but obviously the real cause is the agent.

If you are a persistent reductionist, you can keep arguing. You can say that the mind is the resultant of brain function and the brain function consists of connected neurons and the neurons are made from atoms and molecules, and therefore the ultimate cause is the combined actions of all the components in the brain. This is not a convincing argument at all.

Agency can be “unit” or “cosmic.” According to Yoga philosophy, everything happens within the Cosmic Mind. This prevents science from identifying the Cosmic Mind as a causal factor, because there is nothing outside of the Cosmic Mind. The “unit agency” on the other hand can be integrated into scientific theories during this century. There is hope [18] [19].

Categories

Concepts of “unit agency” and “cognitive core” are related. What is a cognitive core? If an entity has an internal part that partially explains its behavior then that part should be recognized as the cognitive core.

Elementary particles have internal dimensions such as charge and spin that determine the particle behavior as much as the surrounding forces. The charge and spin of an elementary particle are part of its cognitive core. Similarly, the nucleus of an atom, the nucleus of a biological cell, the nucleus of a galaxy all function as the cognitive core. Black Holes are the cognitive cores of space-time.

Cognitive cores interact with each other. Any explanation of change (evolution) requires both concepts: cognitive core and interaction. One obvious example is the evolution of organisms. DNA is the “cognitive core.” Environment is the “interaction.” The evolution of an organism is partially determined by its DNA and partially by the environment.

In theory construction we should pay attention to these categories:

Cognitive core category: charge, spin, symbols, codes, rate-independent memory structures, conservation laws. Any space-invariant and time-invariant law or quantity would belong to this category.

Interaction category: any time-dependent or space-dependent law or quantity.

The “String Theory” framework cannot possibly fulfill its promise of unifying the fundamental physics because it tries to explain everything in terms of dynamics. We cannot explain charge or spin by dynamics. The “cognitive core” and “interaction” categories are ontologically distinct. Rate-independent memory structures (symbols, codes) cannot be explained by dynamics either. We need to find a theoretical framework that pays attention to the cognitive/creative interactive ontology.

The Microvita hypothesis

There is an emerging paradigm that promises to integrate spiritual and mental aspects of the Cosmos to our scientific theories and lead us into new knowledge.

“*Microvita are described as subatomic living entities giving rise to the formation of matter, life and mind in the universe*” [20] [21].

I would emphasize the “vita” part of “microvita.” Fundamental physics should not shy away from the question of “what is organic life?” in the scientific context, and the bigger question of “what is life?” in the cosmological context. Any insights in this area will greatly aid the research efforts on microvita.

The reception of the microvita hypothesis by the mainstream scientists will largely depend on the efforts of microvita researchers to elaborate on the correspondences as well as the differences between the microvita hypothesis and the existing theories of science. Ultimately though, the success of the microvita hypothesis will depend on its explanatory and predictive power.

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