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Current Research in Physical Sciences

18

Fundamental Physics

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18.1 Introduction

In the late 1800s, physics appeared too much as a field that had reached its limit. It was thought that given enough perseverance everything could be understood, based on established laws like electromagnetics, mechanics and hydrodynamics.

Then came a revolution—new fields, for example, quantum mechanics, relativity, elementary particles and later deterministic chaos, nanophysics, changed the way the world was perceived.

As is so often (practically always in research) the case, these fundamental discoveries raised more questions than they could answer, and new branches of research emerged.

Now after about 100 years, there is a conviction that the next “big frontier” is Biology—understanding cells, cell interactions, the genome, proteins, enzymes, etc. There is clearly a lot of truth in this and physics has played an important part in making this possible by developing the fundamentals of electron microscopy, cryotomography, etc.—the tools needed to make advances in biology possible.

But is physics at its fundamental level really understood today? Has the discovery of the Higgs Boson tied up the missing link in elementary particle physics and field theory? Are there serious questions still unanswered or is physics now entering an era of incremental advances with no major breakthrough to be expected?

In this section, we will summarize some of these outstanding major issues, the approaches made towards tackling these and, in particular, the role played by microgravity and space research.

18.2 The Topics

Some of the most intriguing issues in fundamental physics today are the following:

1. On cosmic scales

- The incompatibility of quantum mechanics and general relativity
- Quantum entanglement and action at a distance
- The nature of “dark matter” and “dark energy”
- Constancy of “fundamental constants” in time and space
- Compatibility of inertial and gravitational mass
- Physics inside black holes
- Origin of the universe—quantum gravity

2. On more everyday scales

- Nature of the onset of cooperative phenomena
- Atomistic understanding of fluids
- Origin and onset of instabilities
- Origin and onset of turbulence
- Limits of hydrodynamics—transition to nanofluidics
- Phase transitions (equilibrium/non-equilibrium)
- Critical point phenomena
- Renormalization group theory at the particle level

In other words, the behavior and self-organization of matter at the individual particle level appears to be one of the most interesting regions of contemporary research. This is driven not only by the pure quest of knowledge, but there are also application interests involved as systems get smaller and smaller.

Where does “Space” and in particular “microgravity” enter in our quest to learn more about these fundamental issues? And why is it important to probe these topics further?

To provide an answer to the second question is to look at history. Without quantum mechanics, we would not have semiconductors, computers of a quality provided by the smart phone processors would occupy an indoor basketball court, most medical diagnostic and therapeutic devices (e.g., tomography, pacemakers and hearing aids) would not exist—too large and prohibitively expensive—and many other devices we have become used to, like satellite navigation (which would be useless within hours without knowledge of general relativity), lasers, smart phones and telecommunication, would still be science fiction. So to conclude, every major physics breakthrough has the

potential at some point in the future to become utilized for the benefit of humanity (but also for our detriment, if used wrongly). But this is common wisdom, and the ethics of utilizing or refraining from utilizing knowledge is always going to be with us—whether it is throwing a stone, deploying an atomic bomb or manipulating the genome. Whatever it is, if enough research is done to understand the consequences, then well-founded decisions are possible. If the understanding is faulty, decisions are very likely faulty, too.

So basic research is necessary and (mostly) beneficial if used correctly.

The answer to the second question, “Where does space research play an important or even a decisive role in fundamental physics?” will be summarized next with a few examples. There is not enough scope in this chapter for a complete treatment of all the interesting topics, so some selection has to be made.

18.3 Fundamental Physics in Space

We have listed some of the major outstanding questions in fundamental physics above. Now the utilization of the special conditions offered by space has to be evaluated. Experiments in space are difficult and costly, so the return (in terms of knowledge) has to be correspondingly great. Otherwise the economic reality will soon overcome the scientists’ dreams.

- Space offers a world without gravity. Since gravity is one of the fundamental topics, this fact alone makes space a very attractive proposition for new and novel experiments that cannot be performed on Earth.
- Space is huge. Distance is of great relevance in many fundamental experiments, so here again space provides an attractive environment.
- Space is undisturbed. On Earth many environmental effects “contaminate” measurements, especially as the precision gets increasingly important.

It is not surprising, therefore, that proposals for utilizing the unique space environment have received a strong support throughout the scientific community. Highly rated fundamental research topics are as follows:

- Quantum communication
- Wave-particle duality
- Quantum gases/Bose–Einstein condensation (BEC)
- Atom interferometry
- Constancy of fundamental constants
- Critical point studies in colloids and complex plasmas

- Solidification of colloids in space: Structure and dynamics of crystal, gel and glassy phases

Such a broad and technologically novel approach using the special conditions for research offered by space—promising giant steps in our understanding of physics—was last seen at the beginning of the twentieth century. Today the “enabling factor” is the availability of research under microgravity conditions, in particular the ISS.

One of the major puzzles—perhaps even the major puzzle in physics—is the *incompatibility between “General Relativity Theory” and “Quantum Theory”*. Both theories have been tested and verified to typically 1 part in 10^{10} quantitatively, and must be regarded as very sound. Nevertheless, they are incompatible. A great deal of research effort is spent to understand this, but so far no convincing explanation is forthcoming. One possible resolution of this puzzle is self-gravity, which could destroy the particle wave function. Experiments to test this (e.g., massive particle interferometry, massive BEC interactions) need microgravity.

Another major question concerns the *fundamental constants*, for example, the gravitational constant, the fine structure constant, Planck’s constant, the elementary charge, the proton/electron mass and speed of light. Are these “constants” really universally constant, or do they vary with time on time scales (and accordingly length scales) of the age of the universe? A possibility to test this requires enormously precise and stable clocks. These are usually based on atomic or optical processes. Comparisons can provide new thresholds of constancy or perhaps even measure possible time effects. Stable clocks require microgravity.

Then there is the issue of “*gravitational mass*” and “*inertial mass*”, as discussed in the famous “equivalence principle.” Are they really the same? And how precisely can we measure the predicted gravitational redshift? Such experiments can only be conducted in space if we wish to push the limits of detection to new records.

And last but not least, there is the topic of “*mesoscopic quantum states*” and the issue of the “*wave–particle duality*”. On the one hand, this concerns Bose–Einstein condensates of comparatively huge (billions of elementary) masses, the interactions between such mesoscopic quantum states and the possible effect of self-gravitation and quantum entanglement. Such massive BECs require microgravity in order to grow (and cool) them. On Earth, they cannot be trapped long enough. On the other hand, one would like to investigate wave properties of large particles using modern versions of the “double-slit”

experiment. Since the de Broglie wavelength of particles is inversely proportional to their mass and proportional to their velocity, going to larger particles requires lower velocities (and consequently longer time scales while the particles are moving)—an impossible constraint to maintain on Earth under gravity.

18.3.1 Fundamental Issues in Soft Matter and Granular Physics

“Soft matter” is a name given by the 1991 Nobel Prize Laureate Pierre-Gilles de Gennes to a class of substances (e.g., polymers, colloids, gels and foams) that exhibit macroscopic softness and whose structure and dynamics is not governed by quantum effects (e.g., mesoscopic and supramolecular materials and material assemblies). “*Soft matter*” describes a broad interdisciplinary field covering physics, chemistry and biology, with applications as disparate as paints, new and extreme materials, functionalized (bio) surfaces, etc. Two “recent additions” to this field of soft matter are “complex plasmas” and “granular matter”.

The need for experiments in space again stems from the gravity-free environmental conditions. Under microgravity, some systems are easier to produce, and fragile structures can survive longer. Processes such as convection are absent and therefore cannot inhibit delicate structure formation. Finally, there is the topic of self-organization and dynamical processes at the atomistic level.

Experiments in complex plasma physics have been conducted on the ISS since the very beginning, a period covering 14 years so far. During this long time, the research focus has evolved considerably.

In the early years, the emphasis was on researching the properties of this “new state of matter”—the structure of plasma crystals, propagation of waves, domain boundaries, dislocations, crystallization fronts, melting, etc.—all at the “*atomistic*” level of the motion of individually resolved interacting microparticles, with a temporal resolution fine enough to investigate the dynamics all the way into the range of, for example, the Einstein frequencies in crystals, thus providing access to a physical regime that was previously not accessible for studies at this level. In the last few years, it has been realized that “active” experiments can provide an even bigger and more ambitious scope. The focus now includes the following (remember all studies at the most basic “*atomistic*” level):

- Fundamental stability principles governing fluid and solid phases.
- Non-equilibrium phase transitions (e.g., electro-rheology).

- Phase separation of binary liquids.
- The principles of matter self-organization.
- Universality concepts at the kinetic level in connection with critical phenomena (with the long-term aim of understanding the kinetic origin of renormalization group theory, as developed by a Nobel Laureate Kenneth Wilson)
- The physics (structure and dynamics) on approaching the onset of cooperative phenomena in “small” nano-systems.
- The kinetic origin of turbulence.
- Non-Newtonian physics effects.

So far it has been demonstrated that complex plasmas—with their unique properties of visualization of individual particles and comparatively slow (10^{-2} s) dynamic time scales—can contribute enormously to all these areas of research. On Earth, these studies are complemented by two-dimensional systems since gravity forces acting on the (comparatively heavy) microparticles lead to flat membrane-like assemblies. Two-dimensional studies are of great interest too, so that this complementarity is very valuable. The tasks ahead are to utilize existing and new laboratories on the ISS for dedicated experiments to study these basic strong coupling phenomena and to link the observations to the complementary 3D research carried out in complex fluid studies. The two fields—complex plasmas and complex fluids—may be thought of as different states of soft matter (relating to the “gaseous” or “plasma” state and “liquids” respectively) with correspondingly different properties.

In most of the research topics in dust physics, microgravity provides a unique even essential environment. For one thing, *interstellar, protostellar and planetary ring dust phenomena occur under weightlessness* (so it appears reasonable to also use such conditions in experiments) but in addition, some processes require adequate observation time and controlled environments that cannot be achieved in the Earth’s gravitational field.

At first glance, it seems strange for “*granular matter*”—*close packed assemblies of near-identical and/or size distributed particles*—to be researched in space under microgravity conditions, especially when vibrations are employed to create an artificial gravity. What is mostly not realized is the enormous scope of granular matter in industry (sand, gravel, grains, etc. are the most obvious, and on the finer scale are toner particles, colloids, paints, etc.) and the surprisingly complex issues involved in size sorting, storage, stability, transport, filling, etc. Size sorting can be achieved under

gravity by, for example, vibration, and the larger particles then migrate to the surface—somewhat counterintuitive since they are heavier.

In order to study the processes involved in granular matter physics to understand and model them for the benefit of better and more controlled application on Earth, it is imperative to vary the parameters influencing these processes. One of these parameters, on Earth a constant, is gravity. In space, gravity is absent (or very small). This has several benefits for fundamental studies:

- bigger particles can be used
- time scales for experiments are larger
- the role of fluctuating forces (e.g., vibration) can be studied without “interference” by a macroscopic directed force
- processes can be studied under controlled and variable conditions
- reliable models can be developed that can benefit industrial processes

While all of this seems very “application oriented,” there is also a fundamental aspect to this research. This has to do with the self-organization of “hard sphere” matter. In complex plasmas and complex fluids, we discussed strongly interacting systems with a soft interaction potential (a Debye–Hückel potential in the case of complex plasmas) on the one hand and an overdamped hard sphere potential (complex fluids) on the other hand. Granular matter closes a “systemic gap” by providing a virtually undamped hard sphere system. In this sense, a new regime of parameter space becomes available for studying self-organization processes.

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