a report on
research activity at

The Niels Bohr Institute

Department under the Niels Bohr Institute for Astronomy, Physics and Geophysics

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Introduction:

Theoretical high energy physics concerns the description of Nature at the level of the fundamental constituents of matter. Most research in this field is related one way or another to the so-called "standard model", either by testing it or by going beyond it. But there are also deep connections to modern developments in mathematics (such as topology) and condensed matter physics (such as statistical mechanics).

Within the standard model one talks about four fundamental interactions: (i) the *electromagnetic* forces, responsible for the structure of atoms and molecules; (ii) the weak forces, which explain certain kinds of radioactivity; (iii) the *strong* forces, responsible for e.g. the binding of the quark constituents inside hadrons; (iv) the *gravitational* forces that govern the dynamics of the solar system, and the universe as a whole. The standard model describes the first three interactions by *gauge field theories*: the Glashow-Weinberg-Salam theory of electromagnetic and weak interactions, and the theory of Quantum Chromodynamics (QCD) for the strong forces. In these theories forces are mediated by gauge fields acting between fermion constituents: leptons (such as the electron and its neutrino) and quarks (such as u and d quarks, the constituents of protons and neutrons). Three families of fermions are known, each comprising two leptons and two quark 'flavors'. One important prediction of the GWS model is that in addition to these, the fundamental particle spectrum also contains a scalar particle, the so-called Higgs boson.

Despite its very impressive experimental and theoretical success, the standard model gives rise to a number of unanswered questions. Why are forces based on gauge field theories? Why are these theories based on the particular groups $SU(2) \otimes U(1)$ (for the GWS theory) and $SU(3)$ (for QCD)? Why do leptons and quarks appear in the observed families with the observed structure? Is the number of families predictable? Why do the fermions have the observed masses and couplings? There is a "fine-tuning problem": why are lepton and quark masses so very small compared to the Planck mass. What is the mass of the Higgs boson, and what is the value of the effective ultraviolet cut-off of the electroweak theory? A new and exciting development is the apparent need for small masses (and mixing angles) in the neutrino sector. If correct, are the neutrinos of Dirac or Majorana type?

A particular problem exists in connection with the theory of gravitation, Einstein's general theory of relativity. Though in excellent agreement with all known observations, this theory is not compatible with quantum mechanics at all length scales. How should one construct a quantum field theory of gravity? There is a cosmological constant, which observationally is extremely small – why? The group has made seminal contributions in developing a discretized formulation of quantum gravity that may hold the clue for the answer to these questions.

Even if we put aside such 'fundamental' issues for a while, many questions of detail connected with the standard model require much further clarification. Present research in theoretical elementary particle physics may be broadly classified according to the two main points of view:

(I) One seeks a deeper understanding of the inner workings of the standard model itself, comparing predictions with experiments. A long-standing problem which is still addressed in various forms is that of quark confinement. At high density and temperature there is a transition where confinement is lost, and quarks are liberated. Such problems, which are being confronted at heavy ion experiments, cannot be understood from perturbation theory, and work based on computer simulations is actively being pursued. Computer simulations can also be used to compute zero-temperature observables such as decay constants, masses, etc. The group has been heavily involved in analytical work that allows the determination of such low-energy QCD constants from finite-volume simulations.

(II) One may also seek to throw light on the very origin of the standard model, and try tentative answers to some of the questions mentioned above. At the moment one can view certain theories of *strings* as possible 'theories of everything'. In the last years string theory has undergone a major revolution, with non-perturbative connections hitherto unimagined being revealed. It is now understood that the different string theories may be manifestations of one underlying theory, called M-theory, which also relates the string theories to 11-dimensional supergravity. In addition, a lot of focus has been directed towards the remarkable conjecture that directly links string theory on particular spaces (e.g. anti de Sitter spaces) to certain supersymmetric quantum field theories on their boundary. This correspondence includes applications/realizations of two deep ideas, namely holography in quantum theories of gravity and large N limits of gauge theories. The NBI group been actively contributing from the start to this important development.
Also in the last year have there been new insights in string theory that have had their impact on particle theories, cosmology and quantum field theory in general. Further progress has been made in the connection between supersymmetric quantum field theories and matrix models. In another development, it appears that supersymmetric gauge theories have integrable structures underlying them, which have their dual counterparts in string theory. As a third new direction, it has been found that matrix theory can also be used to describe the decay of D-branes in two-dimensional string theory. Finally, new insights into higher dimensional (super)gravity have been obtained, with applications in black hole physics, cosmology and string theory. The group at NBI has been from the outset actively involved in both of these new research directions.

Additional investigations of the origin of symmetries and the quark-lepton mass spectrum come from a different perspective: Applications of a so-called degenerate vacuum principle have been applied to the Standard Model to obtain predictions for the fundamental parameters of that theory.

In February 2004 the cosmology group from Theoretical Astrophysics Center (TAC) moved to the Niels Bohr Institute and started to operate as a part of the Theoretical Particle Physics and Cosmology group. This collaboration, which is established now in a formal way, has a natural background. At the beginning of the 21st century, fundamental physics and its essential part, cosmology, are confronted with major challenges reminiscent of those encountered a century earlier: two of its foundations, General Relativity and Quantum Field Theory, need to be reconciled.

Cosmology and General Relativity (in particular gravitational wave physics applied to string theory and physics of the Cosmic Microwave Background (CMB)) are the fields in which the implications of modern fundamental physics could leave important observable traces. Another point of close relation between High Energy physics and Astrophysics is the physics of black holes.

Various new areas of the modern cosmology are now being examined and discussed. After the recent Wilkinson Microwave Anisotropy Probe (WMAP) mission, the problems of baryonic charge generation just after the end of inflation, the properties of primordial magnetic fields and particularly its evolution during cosmological expansion seem to be especially important. Prediction of possible relics of the Early Universe ("dark matter") is part of both high energy physic and cosmology.

One of the most impressive results of the WMAP mission is related to discovery of non-gaussianity of the observational cosmic anisotropy signal, firstly detected in the WMAP data by the NBI Cosmology group, and recently confirmed by more than 10 other CMB teams. The issue of non-gaussianity play a crucial role in the analysis of the physical properties of the matter at the beginning of the cosmological expansion and provides a unique opportunity to detect the fundamental properties of space such as non-trivial topology and global asymmetry of the Universe, widely discussed now in the literature. In addition, the non-gaussianity of the observed signal allows us to detect any residues from the synchrotron, free-free and dust emission, and from the point sources, which can contribute to the CMB signal producing corresponding distortion of the CMB information. These have been demonstrated by NBI Cosmology Group.

Future progress in our understanding of fundamental properties of the space and time will be related to the future high precision CMB experiments, particularly PLANCK (start in 2007) and ALMA (2011), which will be able to detect the anisotropy and especially, polarization of the CMB sky with unprecedented angular resolution and pixel sensitivity. Together with DSRI, the NBI Cosmology group has been actively involved in tackling some of the key problems of observations itself (for example, beam properties investigation and its reconstruction in flight), and in developing robust methods of the CMB signal extraction from the observational data.