Prospects for Elementary Particle Physics

The Japan Association of High Energy Physicists (JAHEP)

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1 Present Status of Elementary Particle Physics

In the second half of the twentieth century, remarkable progress was made in particle physics both experimentally and theoretically, which led to the development of the Standard Model of elementary particles. According to the Standard Model, quarks and leptons are the fundamental constituents of matter. They interact with each other by four kinds of fundamental forces; three of them are governed by the gauge principle in the Standard Model. The Standard Model has been tested by many experiments with high precision, and its success has become increasingly firm. Nonetheless, the Higgs particle, which is the origin of the mechanism to generate particle masses, has not been discovered yet. Thus one of the pillars of the Standard Model is still missing and awaits experimental confirmation.

In addition, the Standard Model does not unify the three forces mentioned above, and does not even include gravity. Furthermore, it cannot explain why there are three generations and twelve kinds of quarks and leptons, why they have different masses, and why mixing between different generations occurs. We are thus convinced that the Standard Model is not the ultimate theory of particle physics. We now face the challenge of finding a new direction in particle physics beyond the Standard Model.

Turning to astrophysical observations, we now confront the astonishing fact that known particles, which form ordinary matter, account for only 4% of the total energy density of the Universe. All the rest consists of dark matter (23%) and dark energy (73%), which are not yet identified in terms of particle physics. It is likely that dark matter consists of weakly interacting particles that were created in the early Universe and survived until now. These particles were attracted toward each other by gravity and became seed galaxies. Dark energy is carried by the vacuum and is responsible for the accelerating expansion of the Universe. Dark energy corresponds to the cosmological constant that was introduced by Einstein into the fundamental equation of general relativity. Both dark matter and dark energy should be explained in terms of particle physics in the future.

2 Energy Frontier

In 2008, the LHC experiments will start taking data with a center of mass energy of 14 TeV and will survey new physics at the TeV scale. The ILC will then perform precision measurements in the clean environment of electron-positron collisions to reveal physical principles behind the new phenomena observed at the LHC. The ILC is expected to establish a new paradigm of particle physics, which will be a breakthrough that is as important as past great achievements such as the discovery of anti-particles or the establishment of the gauge principle.

All elementary particles in the Standard Model should be massless if gauge symmetries are not broken. The Higgs particle breaks the gauge symmetries and give masses to elementary particles. Past measurements including those from the experiments at LEP constrain the mass of the Higgs particle to be between 114 GeV and about 200 GeV. Thus the Higgs particle postulated in the Standard Model will be discovered at the LHC. It will be the discovery of the first elementary scalar particle. Elucidation of the properties of the Higgs particle will be the first step in understanding the structure of the vacuum, inflation of the Universe and dark energy, for which some kinds of elementary scalar particles may be responsible. The ILC will scrutinize the production and decays of the Higgs particle, precisely determine its mass, spin, coupling constants to other elementary particles, and its self-coupling. Through these measurements, the ILC will verify that gauge symmetry breaking is the origin of particle masses. Furthermore, there is a possibility of finding the direction in which to extend the Standard Model after uncovering the physics behind electroweak symmetry breaking.

Supersymmetry is regarded as the most promising paradigm beyond the Standard Model. There exist the following pieces of indirect evidence for supersymmetry: (1) the Higgs particle mass, which is not protected by any other symmetry, is kept sufficiently light with supersymmetry; (2) three kinds of interactions, the strong, electric, and weak interactions, are unified at a very large energy scale of 10^{16} GeV with supersymmetry; (3) the lightest supersymmetric particle is a leading candidate for dark matter. Supersymmetry, if discovered, will give an important clue to Superstring theory, which is a candidate for the ultimate unified theory that includes gravity. The LHC is expected to discover evidence for supersymmetry at an early stage in data taking. If supersymmetric particles are within the reach of the ILC, their properties will be understood from precision measurements of their production and decays at the ILC. Through these measurements, we will clearly know if dark matter can be identified as the lightest supersymmetric particles. We also expect that the ILC together with the LHC will find the origin of supersymmetry breaking.

According to the present understanding of elementary particle physics, a light Higgs particle should exist. Many researchers also expect that supersymmetric particles will be discovered at an energy scale below 1 TeV. However, future experiments may encounter something unexpected. In particular, if we find no Higgs particle but some new particle or new phenomenon that is responsible for the electroweak symmetry breaking or the mass generation, it will open a new frontier of physics in both theoretical and experimental studies.

3 Flavor Physics

Even if the light Higgs particle is discovered and supersymmetry is experimentally proven to be a new framework of physics, there still remain the following fundamental questions: why do quarks and leptons of three generations and twelve kinds have different masses ?; why do they mix among different generations ?; why do they violate CP symmetry ? Flavor physics searches for a breakthrough to answer these questions. The Yukawa terms in the Standard Model include many parameters that need to be determined experimentally. Parameters of flavor mixing originate from these Yukawa couplings. Precision measurements of mixing parameters are a necessary step to answer the fundamental questions mentioned above.

At B factories, large CP violation in the B meson system was discovered. It has been proven with good precision that the Kobayashi-Maskawa theory can account for most, if not all, of the flavor mixing and CP violation in the quark sector. At the upgrade of the KEK B factory, we will search for deviations from the Standard Model in some key observables of flavor physics in the clean environment of a lepton collider. Deviations from the Standard Model, if discovered, will quantify the effect of physics beyond the Standard Model. Furthermore, such discoveries may uncover new physics that cannot be detected at the energy frontier. In particular, new sources of CP violation and new right-handed currents, which may arise from supersymmetry or other physics beyond the Standard Model, can be searched for from precision measurements of $b \to s$ transitions that are not measured precisely at the moment. There is also a possibility of detecting effects of the charged Higgs particle in B meson decays. In addition, if lepton-flavor-violating decays such as $\tau \to \mu\gamma$ are discovered, we will be able to develop an entirely new physics of charged-lepton mixing together with experiments for $\mu \to e\gamma$ decays and $\mu \to e$ conversions; this will open a new way to obtain indirect evidence for supersymmetry and the see-saw mechanism. Studies of correlations between $b \to s$ and $\tau \to \mu$ transitions will also allow us to obtain insight into grand unification.

Turning to neutrino physics, the discovery of neutrino mixing at Super-Kamiokande not only verified that neutrinos have masses, but also showed that the mass difference is quite small. This indicates the existence of physics at a very high energy scale if we assume the see-saw mechanism. We have also understood that the flavor mixing of neutrinos shows a different pattern from that of quarks. If future experiments including T2K determine the parameter θ_{13} and reveal that it is not very small, that will open the possibility of observing CP violation in the neutrino sector. Furthermore, there are the following important issues in neutrino physics ahead of us: (1) determining whether neutrinos are Dirac or Majorana particles; (2) determining the mass of the lightest neutrino; (3) determining the mass hierarchy.

In order to ascertain the origin of the flavor structure, it seems likely that understanding of physics at the energy scale of grand unification will play a key role. In the future, with all of the basic precision measurements mentioned above becoming available, the origin of supersymmetry breaking being understood, and proton decay modes being measured, there is a possibility of making a theoretical breakthrough on the origin of the flavor structure. In addition, studies of the flavor structure will provide a basis to resolve the mystery of the disappearance of anti-particles in the early Universe.

4 Future Directions

The most important task of particle physics today is to observe new particles and phenomena in the TeV region, and uncover the underlying physical principles. In particular, we need to determine a new framework of physics from direct production and precision measurements of the Higgs particle and supersymmetric particles, which are longstanding issues in particle physics. This will lead to an understanding of new principles and a new paradigm for particle physics.

In flavor physics, we need to elucidate physics beyond the Standard Model from precision measurements of basic parameters including those of quark and lepton flavor mixing. Furthermore, we will obtain insight into physics at a very high energy that cannot be reached by experiments at the energy frontier.

In addition to the goals mentioned above, it is also expected that these studies of particle physics will lead to a deeper understanding of the beginning and the future of the Universe.

5 The Strategy of the JAHEP

- We, the Japanese HEP community, recognize that physics at the energy frontier is of primary importance. With this understanding, we give the highest priority to the realization of the ILC. Before the ILC experiment commences, we will also promote flavor physics that is complementary to physics at the energy frontier. We should pursue the above two goals as a single master plan.

- Japan is now taking the lead in a wide range of accelerator technologies that are essential to carry out the ILC and flavor experiments. To realize the ILC, we have to facilitate industrialization of state-of-the-art accelerator technologies and boost accelerator R&D for the ILC. For this purpose, we will unify the existing accelerator R&D activities for both the energy frontier and the flavor physics projects.

- In Japan, the K2K experiment, which was the first long-baseline neutrino experiment in the world, was carried out successfully while the KEK B factory has been constantly improving world luminosity records. Furthermore, J-PARC construction will be completed soon. Based on these achievements, we will endeavor to make neutrino and kaon experiments at J-PARC successful, and promote an upgrade of the B factory to achieve a significant breakthrough in luminosity in order to explore new physics that emerges in the phenomena of b, c and τ decays.

- Nowadays, most particle physics experiments and accelerator construction projects are carried out by international collaboration. In order to carry out the projects mentioned above, we will expand internationalization and form stronger partnership with Asian countries and other countries in the world.

6 Short-Term Action Plans

- Physics at the energy frontier:
  Make the LHC experiments a success. Promote R&D aimed toward ILC construction, in particular, establish technologies for mass production and industrialization, and strengthen the R&D organization.

- Flavor physics:
  Complete the construction of J-PARC and promote experiments including T2K and rare kaon decay experiments. Upgrade the KEKB collider to produce world-leading physics results continuously, and utilize the accelerator for ILC R&D.

- The ILC and KEKB have a large commonality as lepton colliders. Share human and material resources in both the accelerator and physics communities, and unify our forces to pursue our master plan.

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