The Final Report of the Subcommittee on Future Projects of High Energy Physics[1]

11 February 2012

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[1] This is an English translation from the original Japanese Report.

Preface

The charge of the subcommittee is to examine future high energy physics projects in Japan within the time scale of more than 10 years into the future and, most importantly, to report on future large-scale projects which should follow those currently operational or under construction.

While the realization of large-scale projects requires an enormous amount of long-term preparation, expectations are rising that important discoveries may be made at LHC or in the neutrino and other experimental sectors within the coming years. It appears that future strategies based on an LHC upgrade and high intensity hadron accelerators are also being developed in Europe and in the United States. Considering these circumstances, Japan should take a leading role in the world by indicating the direction of the future of high energy physics research, from the physics point of view, should these new discoveries be made. It is expected that decisions on, proposals for and the taking of the leadership of such future large-scale projects as ILC will be made in a flexible way, in accordance with the new discoveries.

Another important issue to be resolved is how to advance particle physics research continuously on the various fronts, for example, at SuperKEKB, which is currently under construction or at the medium/small scale experiments at J-PARC and other facilities. Realization of future large-scale projects may depend on the results obtained from these medium/small scale projects. In addition, a coherent strategy for cosmological observations and underground particle physics experiments needs to be adopted since these fields are becoming more and more important. The committee has therefore also surveyed and examined these issues.

Contents

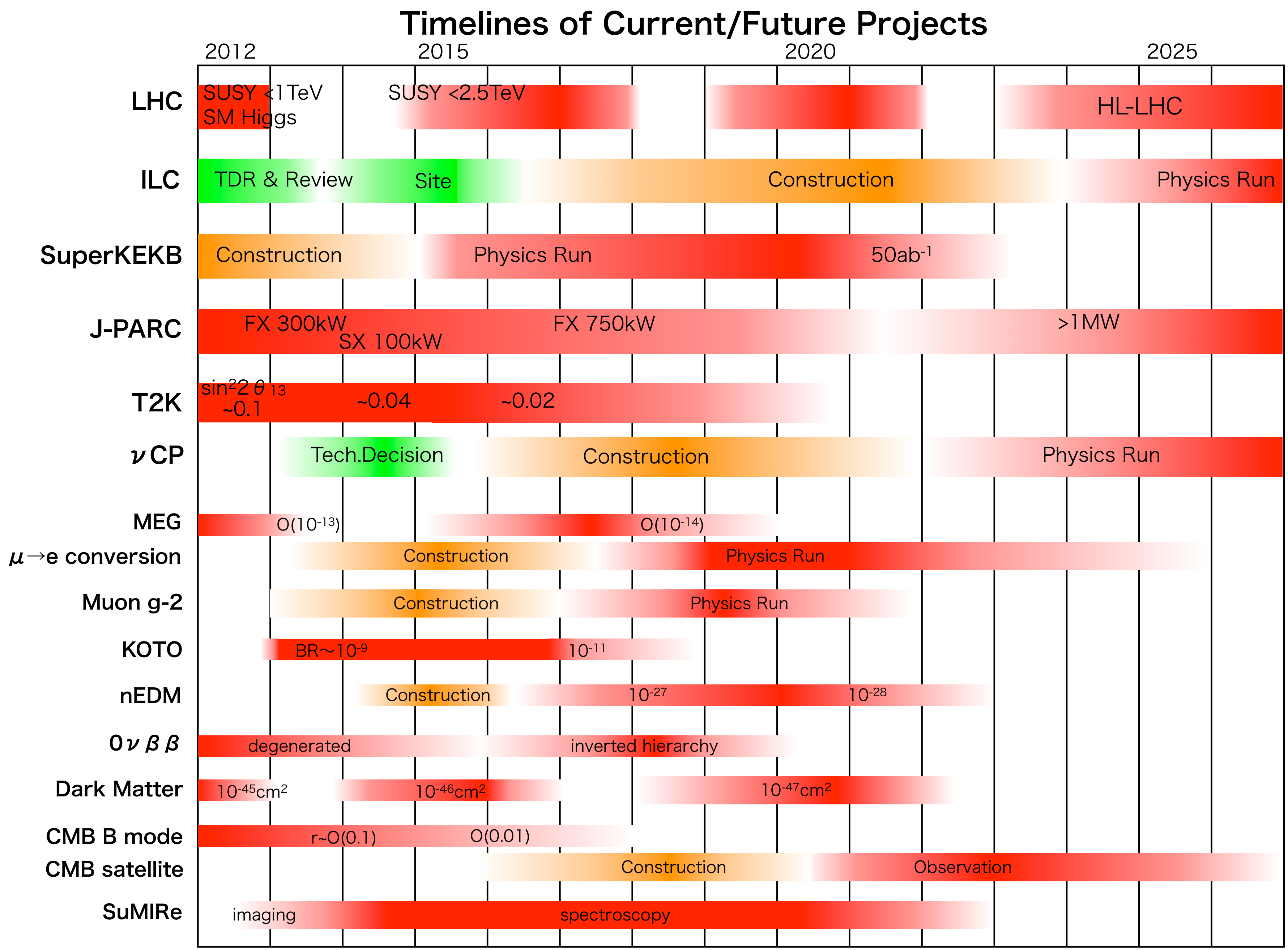
Recommendations

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

- **Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e^+e^- linear collider.** In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time. In parallel, continuous studies on new physics should be pursued for both LHC and the upgraded LHC version. Should the energy scale of new particles/physics be higher, accelerator R&D should be strengthened in order to realize the necessary collision energy.
- **Should the neutrino mixing angle θ_{13} be confirmed as large, Japan should aim to realize a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.** This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

It is expected that the Committee on Future Projects, which includes the High Energy Physics Committee members as its core, should be able to swiftly and flexibly update the strategies for these key, large-scale projects according to newly obtained knowledge from LHC and other sources.

It is important to complete and start the SuperKEKB including the detector, as scheduled. Some of the medium/small scale projects currently under consideration have the implicit potential to develop into important research fields in the future, such as neutrino physics and as such, should be promoted in parallel to pursue new physics in various directions. Flavour physics experiments such as muon experiments at J-PARC, searches for dark matter and neutrinoless double beta decays or observations of CMB B-mode polarization and dark energy are considered as projects that have such potential.


Timelines of Current/Future Projects
2012
2015
2020
2025
LHC
SUSY <1TeV
SM Higgs
SUSY <2.5TeV
HL-LHC
ILC
TDR & Review
Site
Construction
Physics Run
SuperKEKB
Construction
Physics Run
50ab-1
J-PARC
FX 300kW
SX 100kW
FX 750kW
>1MW
T2K
sin22θ13
~0.1
~0.04
~0.02
νCP
Tech.Decision
Construction
Physics Run
MEG
O(10-13)
O(10-14)
μ→e conversion
Construction
Physics Run
Muon g-2
Construction
Physics Run
KOTO
BR~10-9
10-11
nEDM
Construction
10-27
10-28
0νββ
degenerated
inverted hierarchy
Dark Matter
10-45cm2
10-46cm2
10-47cm2
CMB B mode
r~O(0.1)
O(0.01)
CMB satellite
Construction
Observation
SuMIRe
imaging
spectroscopy

1 Current Situation and Future Perspectives

1.1 Current Situation of Particle Physics

Particle physics has developed in order to clarify fundamental principles of interactions between matter and to understand the underlying laws. One of the successes in this field is the standard model of elementary particles based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory, which describes well phenomena below the electroweak scale (approximately 100GeV).

One of the most important questions in establishing a particle physics model at the electroweak scale is to understand the mechanism of electroweak symmetry breaking, which must be spontaneous to be a consistent theory. In the standard model and many other extended models, symmetry breaking is spontaneously induced by the condensation of the Higgs field, with the Higgs boson appearing in the physical spectrum. Although it is the most important target of high energy accelerator experiments such as LHC, the Higgs boson has not yet been discovered. Therefore, there are many unresolved issues in the mechanism of spontaneous electroweak symmetry breaking, which is at the basis of the standard model. Understanding the details of this mechanism is the current primary task of elementary particle physics and with it to clarify the existence of the Higgs boson, and if it exists, to deeply investigate its nature.

The stability of the electroweak scale against radiative corrections is considered as an important key to understanding the mechanism of electroweak symmetry breaking. In general, it is difficult to control radiative corrections to mass terms for scalar fields, and hence the Higgs boson creates tension within the context of the standard model. This is called the hierarchy problem. It implies that a new particle physics model beyond that of the standard model and which is free from the hierarchy problem, may become relevant at the electroweak energy scale. New candidate physics models include supersymmetric models and models with extra dimensions. New particles that appear in these models are important targets for high energy accelerator experiments, as they could lead to important findings in flavour physics and cosmology/astrophysics. Hence the possible impact of these particles should be investigated in fields other than high energy accelerator experiments.

The standard model Higgs boson, if it exists, is expected to be discovered at LHC. High expectations have been raised for the 2012 LHC run, as possible signals of a light Higgs boson that seem consistent with the precision electroweak measurements by LEP etc. were reported in 2011. New coloured particles predicted by various new particle physics models such as supersymmetry or extra dimensions would be copiously produced at LHC. Stringent bounds on the squarks and gluinos with masses below 1 TeV have already been set by the LHC experiments, while significant progress is further expected in the next five years concerning the direct search for these new, beyond the standard model particles. In order to resolve the hierarchy problem in the Higgs sector, interactions both in the top and the gauge sectors need to be extended and new particles will necessarily appear in these sectors. The LHC experiments are currently leading particle physics research in the search for these new particles, and the upcoming results from these experiments, must therefore, be incorporated into any future plan for particle physics research.

In contrast, research into the flavour and CP structure of quarks and neutrinos, an important part of which is carried out in Japan, explores a different frontier to study the origin of matter in the universe and the origin of quark mixing, which is not accessible to the LHC experiments.

It is suggested that quark and charged lepton masses are also generated by Yukawa interactions with the Higgs field. This is specifically supported by the high precision tests of the Kobayashi-Maskawa mechanism at the B-factory experiments, in searches for lepton flavour violating processes, and measurements of the electric dipole moments of the electron and neutron. While new physics at the electroweak scale, if it exists, would create a new flavour structure and new sources of CP violation, there has as yet not been any significant experimental signal. This implies that the new physics may involve a non-trivial mechanism to suppress flavour and CP violation, and that searches with higher precision may be necessary. In particular, efforts to achieve a higher precision measurement, as well as a better theoretical prediction, of the anomalous magnetic moment of muon are being made after an apparent inconsistency was reported as a possible hint of physics beyond the standard model.

The discovery of neutrino oscillations suggests that the neutrinos have tiny masses. This infers the existence of some new physics beyond the standard model to explain their tiny masses. In addition, the pattern of the flavour mixing in the neutrino sector is quite different from that in the quark sector. This suggests that the origin of the neutrino masses is completely different from that of the quark masses. Specifically, if the neutrinos are Majorana fermions, as predicted by the seesaw mechanism, the neutrino masses would then be related to physics at an extremely high energy scale. While neutrino experiments such as the T2K are currently measuring the neutrino mixing angle θ_{13}, there still remain open important questions in neutrino physics: CP violation, Dirac or Majorana type neutrino masses, determination of absolute neutrino masses, and the neutrino mass hierarchy (normal or inverted).

It is of particular relevance that connections between particle physics and cosmology are becoming more and more important. With recent astrophysical and cosmological observations, such as those of WMAP, the cosmological parameters have been more precisely determined. In particular, the energy densities of dark energy and dark matter are known to be approximately 73% and 23% of the total energy density of the universe, respectively, while baryonic matter accounts for a mere 4% to 5%. In addition to this, cosmic density fluctuations are observed to be nearly scale-invariant, strongly suggesting an inflationary origin of the primary density fluctuations. These results pose new problems for particle physics, in addition to providing the basis for constructing the standard model of cosmology. Furthermore, it is impossible to understand the mechanism to generate a matter-antimatter asymmetry, the origin of dark matter, the mechanism of inflation, the nature of dark energy, etc. within the framework of the standard model of particle physics, and clearly some new physics beyond the standard model must have played an important role in the evolution of the universe. New knowledge of physics beyond the standard model, which both present and future high energy experiments such as LHC and ILC are expected to provide, is indispensable in solving these cosmological problems.

1.2 Future Perspectives of Particle Physics

The energy frontier experiments at LHC and its upgrades will lead particle physics through direct searches for the Higgs boson and new particles such as those predicted by supersymmetry. Determination of the mass scales of the Higgs boson and the new particles through these direct searches will be especially important in planning future particle physics projects.

For an understanding of the mechanism of electroweak symmetry breaking and also the origin of quark and lepton masses, we need to know the quantum numbers and interactions of the Higgs boson in addition to its mass. An excess of a Higgs-like signal has been reported at a mass of around 125 GeV; in this mass region there is a rich decay pattern. Some of the decay processes induced by loop diagrams are sensitive to new physics, so if one finds a deviation from the standard model prediction of the branching ratios of the Higgs boson, it will help to determine and optimize the centre of mass energy of future colliders. A light Higgs boson is within the reach of ILC, and more detailed studies compared to LHC can be performed.

New particles may be found in due course with the increase of the energy and luminosity of LHC. The interactions and quantum numbers must be determined in order to reveal the symmetry behind these new particles such as supersymmetry. In turn, these symmetries may lead to further particle searches. This may also provide a clue to the hierarchy problem in electroweak symmetry breaking. If the masses of these new particles are within the reach of the lepton colliders such as ILC, the nature of the particles can be studied under relatively low background conditions. LHC therefore has a high potential for discovering new coloured particles, while the ability to discover particles without colour charge is rather limited. Therefore, when a new particle is found at LHC, lepton colliders would also be necessary to understand the nature of such particles.

In addition to the energy frontier experiments, precision measurements of hadronic and leptonic flavour changing processes and electric dipole moments have also been useful tools in constructing and establishing the standard model. They are expected to play important roles in the future study of new physics beyond the standard model, which is expected to exist at the electroweak energy scale.

Since the heavier quarks couple more strongly with the origin of electroweak symmetry breaking, they might be more sensitive to new physics. On the other hand, since the quark mixings are well described by the Cabibbo-Kobayashi-Maskawa matrix, contributions from new physics to flavour-changing processes in B-meson decays are smaller than 10~20%. Thus, various B-meson decays should be studied with higher precision in order to understand the details of flavour changing processes and CP violation in these processes. The LHCb and the SuperKEKB experiments both have high sensitivities to possible new physics signals in differing decay modes, and hence are expected to play a complementary role for each other. Such indirect searches for new physics in the form of flavour physics are important, independently of the direct searches at LHC, and will help to gain knowledge of new physics beyond the electroweak energy scale together with the results from LHC.

Although lepton flavour and CP symmetry are not strict symmetries of nature, the branching ratios for the charged lepton flavour violating processes and the electric dipole moments of leptons and hadrons are strongly suppressed in the standard model. However, there is no reason to suppose that such symmetry breaking is insignificant also within the framework of new physics at the electroweak energy scale; hence studies on charged lepton flavour violation and electric dipole moments might show high sensitivity to such new physics at the electroweak energy scale. By searching for the breaking of flavour and CP symmetries in flavour physics experiments such as those at J-PARC and the MEG experiment, clues to new physics could be discovered. As for the baryon- and lepton-numbers, which might be violated in physics at a very high-energy scale (e.g., Grand Unified Theories), searches for proton decays may provide important implications.

Observation of the neutrino oscillation strongly suggests physics beyond the standard model. To understand this in detail, further intensive studies of the properties of the neutrinos are necessary. If the neutrino oscillation experiments, such as the T2K experiment, find a sizable neutrino-mixing angle θ_{13}, this may also provide the opportunity to discover CP violation in the neutrino sector. All the CP violation so far observed originates uniquely from the complex phase in the Cabibbo-Kobayashi-Maskawa matrix. Discovery of CP violation in neutrino oscillations would indicate a new source, other than that in the quark sector. In addition, searches for neutrinoless double β-decays ($0\nu\beta\beta$) by, for example, KamLAND-Zen are important in settling the issue of whether the neutrino mass is of a Majorana- or Dirac-type. If the neutrino mass is of a Majorana-type, it strongly supports the notion that the tiny neutrino masses are a natural consequence of the seesaw mechanism, and that the baryon-anti-baryon asymmetry in the universe is generated in a leptogenesis scenario. It is considered as one of the most important goals of future particle physics to reach a unified understanding of the origin of the flavour structure and the CP violation by combining the knowledge of the lepton mass matrix with that of the quark sector.

Significant progress is also expected in gaining knowledge of the properties of dark matter. There are various candidates for dark matter: weakly interacting massive particles (WIMPs), coherent oscillation of scalar condensation, etc. Among them, there is also a scenario that thermally produced WIMPs freeze-out from the thermal bath at a temperature slightly below its mass, to become dark matter. In order for such thermally produced WIMPs to be the main component of dark matter, the pair annihilation cross section of the WIMPs should be at about 1 pb, which corresponds to the cross section obtained by exchanging a particle with a mass of order 100 GeV to 1 TeV. Thus, the dark matter particle may be embedded in a particle physics model that resolves the hierarchy problem. In fact, the cross section of supersymmetric dark matter particles scattering off nuclei may be large enough to be detected by current and future direct dark-matter detection experiments. Hence confirmation of dark matter particles by direct detection experiments such as the XENON and XMASS is therefore anticipated.

At LHC, the dark-matter particle may be found by using the missing transverse momentum information. With the discovery of such a candidate particle, detailed studies of its properties are necessary to confirm whether it is really consistent with the dark matter in the universe. For the detailed study of the properties of a dark matter candidate, ILC can also play an important role. With such studies, important information in understanding the thermal history of the universe will be provided.

Progress is also expected in the understanding of the evolution of the universe through inflation. In particular, if the tensor-to-scalar ratio is larger than about 0.1, the Planck satellite would be considered able to detect the B-mode polarization of cosmic microwave background, which strongly supports the inflationary scenario of the universes evolution. The amplitude of the B-mode provides information on the energy scale of inflation. If the tensor-to-scalar ratio is larger than about 0.01, various successive experiments such as POLARBEAR would be able to observe the B-mode polarization.

2 Energy Frontier

2.1 Overview

Research at the energy frontier aims at discovering new particles and phenomena, as well as determining their properties and the laws of nature governing them. The numerous accomplishments in this area include the discovery of quarks, leptons, and gauge bosons, the measurement of their quantum numbers and coupling strengths, and the determination of the symmetries of the interactions and the number of particle generations. Precision measurements performed at LEP and SLC provided firm ground for the gauge sector that forms the basis of the Standard Model. The Higgs and Yukawa sectors remain as yet, uncharted territory. It is expected that, through the discovery of the Higgs boson and its properties, new interactions different from the gauge interactions will be studied, leading to the search for new physics beyond the Standard Model. At the highest energies, the search for new physics involves the direct production of new particles and phenomena.

In order to study higher energy reactions at hadron colliders such as LHC, either beam energy or luminosity can be increased, the latter increasing the reaction rates of high-energy partons. Since the beams at hadron colliders consist of protons and/or antiprotons, which are composite particles, only a fraction of their energy participates in the reaction, while the rest undergoes fragmentation and becomes background. The Higgs boson can therefore be discovered through reconstructing its mass from the photons and leptons, which are emitted when it decays. New particles accompanied by missing transverse momentum, such as supersymmetric particles, may be detected in a wide energy range when they are copiously produced via the strong interaction.

In contrast, to reach even higher energies with a lepton collider, candidates such as a linear collider, which does not suffer from losses due synchrotron radiation of electrons and positrons causing inefficiencies in their acceleration, or a muon collider employing the heavy lepton must be used. Since all the energy is converted into the reaction in lepton colliders, the final states can be measured precisely. In addition, the beam energy and the polarization can be adjusted to separate the intermediate and final states of the interactions, enabling the determination of the symmetry in the reaction as well as the mass and quantum numbers of the new particles. New particles produced from both electroweak and strong interactions can be searched for; after their discoveries, their properties can be studied in detail in a low background environment.

2.2 International Linear Collider

The ideal machine to study the Higgs boson, whose discovery is anticipated at LHC, is considered to be the International Linear Collider (ILC). At ILC, linear accelerators will be installed in an underground tunnel to accelerate the electrons and positrons in opposite directions for head-on collisions. Initially, the experiment can start with a shorter accelerator providing the minimum energy required for the target of the physics study, subsequently extending its length to increase the energy. At ILC, the targeted collision energy in the first stage is between 200 to 500 GeV (corresponding to a 30 km straight section) with a future option to upgrade it to 1 TeV within scope.

The first priority is to study the Higgs boson; the main objects of study include the following: (1) mass, (2) spin and parity, (3) coupling to gauge bosons, (4) decay branching ratios, (5) total decay width, (6) Yukawa coupling to the top quark, and (7) self-coupling. The main production process of the Higgs boson at ILC is one accompanied by a Z boson. If the mass of the Higgs boson is around 120 GeV, the tasks (1)-(5) above can be optimally performed at a centre-of-mass energy of around

250 GeV. Tasks (6) and (7) involve the production of top quarks or multiple Higgs bosons and so require a centre-of-mass energy of close to 500 GeV. The number of Higgs bosons produced will exceed 10^5, studied in an environment with a good signal-to-noise ratio. Thus its mass can be determined to a precision of within a few tens of MeV, while the gauge couplings can be determined to within 1 percent. From the branching ratio measurements, the Yukawa couplings to the bottom and charm quarks and to the tau lepton can also be determined to within a few percent. Even if the Higgs boson decays to invisible particles such as dark matter, the measurements can be performed in a model-independent manner through the analysis of the recoiling Z-boson. Given the mass precision to within a few tens of MeV, the Standard Model predicts the value of other observables to be within 1 percent. By comparing them to the observed values, the Higgs and Yukawa sectors of the Standard Model can be tested to high precision. A single measurement differing from the predicted values would signal the discovery of new physics beyond the Standard Model.

New particles such as dark matter that may escape detection at LHC could be discovered at ILC through their direct production. If the collision energy exceeds the production energy threshold, their discovery would be certain. For new particles that do not create a mass peak, such as supersymmetric particles and those that do not possess a colour charge, such as a light dark matter particle, it would be considered hopeless to discover them at LHC. At a lepton collider however, these new particles without a colour charge can be discovered via their decay products or through initial state radiation, so enabling the properties of dark matter particles and others to be determined through detailed measurements. New particles or phenomena that are currently not predicted may also be discovered. Furthermore, ILC possesses a sensitivity to new physics through comparison with precise theoretical calculations, such as the Z' bosons up to and exceeding 10 TeV. Schemes are currently being developed to experimentally test the Grand Unified Theories, which are important for the very early universe, by combining measurements from the hadron collider experiments.

Overall Plan, Framework, Budget and Schedule

ILC will be able to make significant progress, not only in the understanding of elementary particle physics and cosmology, but also in advanced technologies such as super-conducting accelerators. Furthermore, by forming a new international research centre integrating academic, educational, and technological activities, ILC would facilitate these discoveries.

From 2000 to 2002, the world-wide high energy physics community, mainly represented by Asia, U.S. and Europe, established a consensus with the aim to jointly construct an electron-positron linear collider as a priority for its next main project. According to the agreement, the physics studies of the design of the accelerator and detectors for ILC have been performed as world-wide international activities. Notably, after GDE (Global Design Effort) was established in 2005 by major particle physics laboratories operating high energy accelerators (KEK, DESY, Fermilab), global activities have been promoted intensively to further the detailed technical design of ILC. More than 1000 researchers and engineers, and more than 300 laboratories, universities (over 40 in Japan), and many private companies have participated in an R&D effort. In this process the Asian research centre, the Japanese ILC team including KEK play a leading role. A synchrotron light facility, based on superconducting accelerator technology developed by the ILC project, is now under construction in Germany. In the U.S., a large project has been promoted to develop the super-conducting accelerator for ILC, and concurrently for a high power proton accelerator. For detector R&D, two large international collaborations, corresponding to two experimental proposals have work in progress. In addition, FALC (Funding Agency for Large Colliders) which is an information exchange forum for administrative agencies has been setup and various issues for the realization of

ILC have been actively discussed.

Following the reference design in 2007 by GDE, GDE is now concentrating on the design optimization and industrialization of the accelerator technology. Taking into account also initial results from LHC physics, a TDR (Technical Design Report) will be published in 2012. If the construction site is determined with international consensus among those countries within 3 years of the TDR publication, the ILC detector and accelerator construction could start in 2015. After a 7 to 10 year construction period, ILC operation and experimentation will be able to start from 2025 onwards. In the reference design, the construction costs and the annual operation costs were estimated to be approximately 6.7 billion USD and 200 million USD, respectively for a 500 GeV ILC version. Some cost reduction is expected as a consequence of technological innovations, technical design optimizations, and collision energy justification based on the LHC results.

ILC Detector Technology R&D

ILC detector technology R&D is concurrently undertaken by two design teams, ILD and SiD, as key international collaborations. To improve the hadron jet reconstruction scheme (Particle Flow Algorithm) invented in LEP experiments, a pixel vertex detector, a large solid angle tracking detector and a fine segmented calorimeter which is able to separate each shower particle, are being developed. In Japan a version with a vertex detector surrounding the interaction point, a calorimeter, and a large TPC tracking detector are being developed. In close collaboration with the theory group, physics studies and optimization of the detector concept are being advanced. Japanese physicists are participating mainly in the ILD conceptual design and will lead the ILC physics and detector study in Asia and also organize an international collaboration with European and U.S. counterparts. Experience of detector operation in Belle II, ATLAS and the T2K near detector have provided useful information for important components of ILC detectors such as sensors.

ILC Accelerator R&D

In terms of ILC accelerator R&D, important technologies such as polarized electron sources, positron beams, flat super-low emittance beams, high gradient super-conducting accelerators and nano-beam focusing are being developed. In ILC, a 1.2m, 9 cell super-conducting accelerator module, made of Nb and cooled down to 2K is operated at 31.5 MV/m. ILC consists of 1,700 cryomodules and 15,000 cavities. In order to fabricate such a large number of cavities within a reasonable time period and at a reasonable cost, while satisfying the required performance, the manufacturing process has to be stringently controlled. One of the goals in 2012 is to achieve a more than 90% cavity production yield, satisfying the 35 MV/m gradient requirement, which has almost now been met. The current main issue is further cost reduction; industrial production of ILC construction has been intensively furthered by designing and optimizing the production lines of cavities and cryomodules, and constructing a pilot plant for the production systems engineering.

KEK operates key test facilities for ILC: The Accelerator Test Facility (ATF) and the Super-conducting Test Facility (STF). The Aim of STF is to demonstrate the performance of the ILC main linac cryomodule (a cryogenic chamber containing the super-conducting accelerator part). Two cavities from Europe, two cavities from the U.S. and four cavities from Japan were assembled into one cryomodule and the operational test was carried out at STF from 2010 to 2011 with an average gradient of 26 MV/m being achieved. An optical camera was specially designed and developed to investigate the properties of the inner surface of the ILC cavity. By observing the irregularities on the cavity inner surface with this camera, some difficulties that caused cavity performance degradation were identified.

The aim of ATF is to generate a flat super-low emittance beam by radiation damping, and develop and demonstrate the beam diagnostic technology and the final focus system with the beam. ATF has already achieved a 0.015 mm･mrad vertically normalized emittance, which surpasses the ILC requirement. The current issues under study are to realize and control a 35 nm beam size and establish beam diagnostic technology at the prototype ILC final focus system (ATF2).

A polarized electron source has been developed by SLAC and Nagoya University with a 90% polarization already having been achieved. The issues here are generating a 1ms long pulse and developing a driver laser system. Further related activities to the positron generation are the R&D of a super-conducting helical undulator and a prototype test of a positron generating target all of which are in progress. An alternative positron source using the electron beam has been proposed in Japan.

2.3 LHC Upgrade

At present, there are two experimental groups, ATLAS and CMS, which are studying the electroweak energy scale physics at LHC, CERN. Their primary goal is to search for new phenomena beyond the Standard Model. Sixteen institutes in Japan are participating in ATLAS and have worked on construction of the beam focusing magnets in the interaction region, the solenoid magnet used for the charged particle spectrometer, the silicon strip detector, the muon trigger chambers and have been playing important roles in the various stages from installation to operation. Also significant contributions are being made on the data processing side, as a Tier-2 centre of the GRID computing.

One important goal of LHC is to explore new physics and new phenomena at the electroweak energy scale by making the best use of the high collision energy. It is therefore important to extend the exploration region to a higher energy by increasing the luminosity. An increase in the integrated luminosity from 100 fb^{-1} to 1000 fb^{-1} would allow an improvement in sensitivity for a search for new physics, for example, in the mass reach of the squarks from 2.5 TeV to 3 TeV, or in the mass scale in the case of Extra Dimensions from 9 TeV to 12 TeV. Once new particles or phenomena have been discovered, LHC will be the only machine which can provide an opportunity to study the new findings, that is until ILC is built and starts up.

In the long term plans for LHC, approximately 300 fb^{-1} of data are expected to be collected at the centre of mass energy of 14 TeV by 2022. The high luminosity project (HL-LHC) will then start up to shorten the luminosity doubling time and also to compensate for the aging accelerator components near to the interaction region due to radiation. The aim is to accumulate an integrated luminosity of 3000 fb^{-1} by 2030. To achieve this goal, luminosity levelling, that is to keep the beam for longer at a lower instantaneous luminosity ($5\times10^{34}cm^{-2}s^{-1}$), rather than running at the maximum instantaneous luminosity with a much shorter beam life time, may be adopted to gain in integrated luminosity. This scheme is likely to require crab cavities.

The key elements of the luminosity upgrade are the development of the strong focusing magnets, the injector upgrade to increase the number of protons, and the introduction of the crab crossing. The current focusing magnets near the interaction region were developed and built by the collaboration of KEK and Fermilab. Those magnets included, as well as all the magnets around the interaction region will be replaced. However, the conventionally used material does not meet the specifications of the magnetic field strength (which is 13 to 15 Tesla), and new materials are being developed in Japan, US, and Europe. In addition to the design of the optics which has already been started, the task sharing in the international collaboration is also underway. In the new materials development for the magnets, attention will be paid to the wide range of applications, such as the

LHC energy upgrade. Only KEKB to date has succeeded the crab crossing in the world, and therefore Japan's large contributions in this area as well as in the development of the superconducting magnets are expected.

For the HL-LHC, the whole inner tracker of ATLAS will be replaced. There are two main issues here, radiation hardness, and a finer granularity necessary to cope with the high occupancy due to the higher luminosity. In order to be more rate tolerant, all the trackers will be composed of silicon detectors. The innermost layers will be of silicon pixels while the outer layers will be comprised of silicon strip detectors. Since there is a strong vendor of silicon sensors in Japan, a strong commitment to the development of the silicon detectors is expected. In fact, Japanese groups have already started to develop radiation hardened sensors. Apart from the inner tracker, also an upgrade of the readout electronics for the calorimeter and muon detector, the improvement of the muon trigger, and the rebuilding of the forward shield are planned. Japanese groups are heavily involved in the development of the inner tracker, the trigger improvement using the inner tracker, and the muon trigger and its readout electronics.

The developments in the above technology for HL-LHC could also be useful for the LHC energy upgrade. There is an idea in place to increase the centre of mass energy of LHC to 33 TeV, called the High Energy LHC (HE-LHC). In order to achieve such a high energy, the present magnets composed of NbTi cables must be replaced by ones made of new superconducting materials. Workshops to develop such materials have been held since 2011. In 2013, prototype HTS magnets will be developed under the EuCARD2 programme run by EC-FP7. It is important to promote basic R&D in Japan on new superconducting materials such as Nb_3Al and their application in accelerator magnets, also with a view to a wider field of application.

2.4 Other Projects

The Compact Linear Collider (CLIC) and a muon collider are under investigation for the energy frontier physics surpassing the ILC energy region. The CLIC study will be continued amounting to more than 20 years while it is expected that the muon collider will take 30 years for full realization of the project. As a further long term future project, laser-plasma acceleration is also under study. Currently, there is no completed accelerator system with this technology and basic proof-of-principle tests of self-injection and plasma "afterburner" are being considered. Recently, a new laser technology has been making rapid progress with possible laser-plasma acceleration being realized if some breakthroughs are made in a multi-stage acceleration scheme.

CLIC

CLIC is an electron-positron linear collider for the particle physics research up to a multi-TeV centre of mass energy exceeding that of ILC. The maximum centre of mass energy goal is 3 TeV for the nominal value that is determined by a technology limit rather than a physics motivation. CLIC is being studied within the framework of a world-wide collaboration consisting of CERN and 42 institutes in 21 countries. Although the CLIC project is conceived as a future electron-positron collider post ILC, a more urgent need by particle physics research at the multi-TeV energy might arise depending on the results of the LHC experiments.

Just as for ILC, the main components of CLIC are electron and positron sources, a damping ring, accelerating structures, RF power sources, and an interaction region. CLIC, however, adopts a two-beam acceleration concept to use microwaves generated by decelerating a low energy, high current electron beam, as an RF power source, instead of klystrons, to accelerate low current beams to high energy. In the two-beam acceleration scheme, the driver beam of 101 A is accelerated up to 2.38

GeV by 1 GHz klystrons and a delay loop and a two-stage combiner ring compresses the duration between the beam pulses in order to make an appropriate pulse structure for the main beam. The compressed driver beam is decelerated to 240 MeV, conversely, the main beam of 1 A is accelerated from 9 GeV to 1.5 TeV. The frequency of the accelerating structures is 12 GHz (X band). Difficulties anticipated in the CLIC technology are the pulse compression technique with combiner rings, the transfer of the RF power from the drive beam to the main beam, and the development of accelerating structures for the very high gradients of 80-100 MV/m.

Power consumption is about 240 MW for a centre of mass energy of 500 GeV (luminosity of $1.4\times10^{34}cm^{-2}s^{-1}$) and 560 MW for 3 TeV (luminosity of $2\times10^{34}cm^{-2}s^{-1}$) version. The two-beam acceleration scheme at 12 GHz frequency may not be advantageous in comparison with ILC and the power consumption in the current design which is equal to or larger than that of ILC. The key issue in the CLIC two-beam acceleration scheme is an efficient transfer of beam power to reduce the power consumption while trying to avoid the technical difficulty of using X-band klystrons.

Muon Collider

The muon is a lepton similar in nature to the electron. Since the associated synchrotron radiation can be reduced due to the heavier mass of muon, a compact circular accelerator for muons can be realized up to a multi-TeV centre of mass energy. Another advantage of such a muon collider compared to electron-positron colliders is the possibility to observe an s-channel resonance production of a Higgs. The difficulties of the muon collider are in the production of high intensity muons and accelerating them within the muon lifetime of 2 μsec, while colliding them with similar luminosity to ILC. The nominal centre of mass energy is 4 TeV (2 TeV + 2 TeV) in the current plan. Muons are obtained from decays of pions that are produced by bombarding a 16 GeV proton beam onto a production target. A new technique called ionization cooling proposed by Skrinsky, Parkhomchuk, and Neuffer is utilized to make the hot muon gas into a cold beam with low emittance for luminosity. Muons of ~100 MeV thus produced are quickly accelerated in multi-stage accelerators to 2 TeV in order to increase their lifetime in the laboratory frame. The primary issue in the realization of a muon collider is to establish practical technologies to produce and cool down high intensity muons sufficiently, although many other problems such as radiation shielding against high energy muon decays also needs to be resolved.

3 Neutrino Oscillation

3.1 Neutrino Oscillation and Proton Decay

One goal of neutrino physics is to understand "the origin of neutrino mass and the mixing" and to find a hint of new physics at ultra-high energies, such as that predicted by Grand Unified Theories, beyond the standard model of particle physics. A next-generation neutrino experiment aims to determine the mixing matrix of neutrinos with high accuracy including a test of CP symmetry by measuring neutrino oscillations precisely. At this moment in the study of neutrino oscillations, an important issue is the determination of the size of the neutrino mixing angle θ_{13} since its size limits the possibility of neutrino CP-violation experiments. In addition, it is possible to study Grand Unified Theories by searching for proton decay using a large-scale detector for neutrino experiments. The next-generation neutrino detector will be required to have a sensitivity to a proton lifetime as long as 10^{35} years, a requirement consistent with the predictions from many models of Grand Unified Theories.

3.2 Current Status

Flavour Mixing

Understanding of the properties of neutrinos has been dramatically advanced in the last 14 years since Super-Kamiokande discovered neutrino oscillation in 1998. Today it is an established fact that neutrinos have finite masses and mix. Past experiments have constrained the neutrino oscillation parameters; $|\Delta m_{23}^2| \fallingdotseq 2.35\times10^{-3}\mathrm{eV}^2$, $\theta_{23} \fallingdotseq 45°$, $\theta_{12} \fallingdotseq 33°$, $\Delta m_{12}^2 \fallingdotseq 7.6\times10^{-5}\mathrm{eV}^2$. The mixing angle θ_{13} has not had a major development after an upper limit was given by the reactor-neutrino experiment Chooz in 1999. In 2011 the T2K experiment found an indication of non-zero θ_{13} at 2.5σ significance with $0.03 < \sin^2 2\theta_{13} < 0.28$ (90% C.L. for $\delta=0$), which was supported by the results reported by the MINOS and Double Chooz experiments. It is expected that the measurement of θ_{13} will further be improved in two to three years by the neutrino experiments such as T2K and Double Chooz.

Proton Decay

Super-Kamiokande, the largest neutrino detector in the world, has taken the lead in the search for proton decay. As for the proton lifetime, lower limits on individual decay modes are as follows; $p\rightarrow e^+\pi^0$: 1.3×10^{34} years, $p\rightarrow\mu^+\pi^0$: 1.1×10^{34} years, and $p\rightarrow\nu K^+$: 4.0×10^{33} years. A major decay mode in a typical Grand Unified Theory is $p\rightarrow e^+\pi^0$, while $p\rightarrow\nu K^+$ is typical of a supersymmetric Grand Unified Theory. In many theories, similar lifetimes ranging from 10^{34} through 10^{35} years are predicted.

3.3 Future Planning

The possibility that θ_{13} may be determined within a few years by the ongoing neutrino experiments such as T2K and Double Chooz have raised high expectations. If a large neutrino mixing angle θ_{13} is established, the aim should be to realize a large-scale neutrino detector through international cooperation, together with a reinforcement of the J-PARC accelerator, toward studies on CP symmetry through neutrino oscillations. The J-PARC accelerator is expected to achieve its design power of 750 kW in approximately five years, and a feasibility study to further increase beam power will be continued. As for the detector, the experimental plan should be clearly prioritized by studying the feasibility of the plan in detail, including budget and construction period, after evaluation of the sensitivity reach of the next-generation long baseline neutrino oscillation experiment and its physics potential. Also the detector should have sufficient sensitivity to proton decays which would be direct evidence of Grand Unified Theories.

CP Violation Measurement

The most suitable channel for a CP violation search is $\nu_\mu \rightarrow \nu_e$ appearance. This is due to the fact that it needs to be an appearance channel, since CP violation effects are not present in the disappearance channel. In addition, the CP conserving term is small due to the small θ_{13} in the $\nu_\mu \rightarrow \nu_e$ channel while the CP violation effect is relatively large. There are basically two experimental methods: (1) measuring the asymmetry of ν_e appearance probabilities between neutrinos and anti-neutrinos, and extracting the CP violating terms which are proportional to $\sin\delta$; and 2) measuring the energy spectrum of ν_e appearance precisely by using the fact that the energy dependence of the δ term is different from the θ_{13} leading term. In either method the sensitivity needs to be 10 to 100 times higher than that of the T2K experiment for ν_e appearance, since the CP violation effect appears as a second order effect of small ν_e appearance probability. In order to have a reasonably high discovery potential for a wide range of δ, a MW-class high power accelerator and an extremely large detector with high sensitivity are needed. In Japan the following two plans are under study; (a) a megaton-class water Cherenkov detector, Hyper-Kamiokande, placed in Kamioka, 295 km from J-PARC to employ mainly method (1); (b) a 100 kilo-ton liquid argon TPC placed in Okinoshima, 658 km from J-PARC to employ mainly method (2).

J-PARC Accelerator and Neutrino Beam

J-PARC is a high intensity proton accelerator facility in Tokai, in the Ibaraki Prefecture, constructed jointly by JAEA and KEK. It consists of a set of accelerators: LINAC, 3GeV Rapid Cycle Synchrotron (RCS), and Main Ring (MR). For a long baseline neutrino oscillation experiment, a neutrino beam is produced by using protons accelerated up to 30 GeV in MR, with a design power of 750 kW. In 2009, the J-PARC construction was completed including the neutrino beam facilities enabling the start of beam operation. A stable beam was provided for the T2K experiment from January 2010, and a beam power of 145 kW was achieved in March 2011. Although the facilities were damaged by the Great East Japan Earthquake, the operation was resumed again in December 2011.

It is the main aim that the design beam power of 750 kW should be achieved in approximately five years by realizing a high current and high repetition rate as described below. The higher current of MR (increasing protons per bunch) is to be realized by upgrading the ion source and RFQ of LINAC, by upgrading the LINAC energy to 400 MeV, by decreasing the space-charge effects and by enhancing the power of RCS. Furthermore, the RF upgrade of MR and the upgrade of magnet power supplies will lead to the realization of a high repetition rate of MR. The present repetition period of about 3 seconds will be shortened to 1 second. R&D and the production of components are currently in progress.

The study to realize a beam power in excess of 1MW is also underway. Various ideas such as the possibility of building a new booster ring to raise the injection energy to MR are under consideration. In order to realize the power above 1MW, it is necessary to advance necessary R&D by incorporating the experiences of high intensity operation and optimizing methods and designs.

Hyper-Kamiokande

Hyper-Kamiokande is a supersized next-generation water Cherenkov detector, which utilizes key technologies established in Super-Kamiokande and has a total mass expanded to 1 Mton. Hyper-

Kamiokande has a wide-range of physics goals: a measurement of neutrino CP violation by using neutrino beams from J-PARC, search for proton decay, determination of the neutrino mass hierarchy and a measurement of neutrino CP violation by atmospheric neutrino observation, and the observation of cosmic origin neutrinos.

Hyper-Kamiokande is comprised of two column-shaped detectors each 48 m wide, 54 m high, and 250 m long, located at 650 m underground of Nijuugo-yama mountain (1750 m water equivalent), 8 km south of Super-Kamiokande. The distance from J-PARC is also 295 km just as for Super-Kamiokande. 99,000 20-inch photomultiplier tubes are used with a total photon-sensitive area coverage of 20% of the inner water tank. The expected detector performance is as follows; misidentification probability for 500 MeV electrons and muons less than 1%; the momentum resolutions of 5.6% for electrons and 3.6% for muons; the detection efficiency for electron-neutrinos from the J-PARC neutrino beam 64%; rejection power of more than 95% for π^0 produced by the neutrino beam.

Hyper-Kamiokande has a 25 times larger fiducial volume than Super-Kamiokande. It measures neutrino oscillations with high statistics and accuracy by using the J-PARC neutrino beam with an extremely high sensitivity to CP violation in the neutrino sector. Assuming the J-PARC neutrino beam data of 8 MW×year [2] (corresponding to approximately ten years at 750 kW of beam power), the CP violation parameter δ can be determined to an accuracy of better than 18 degrees. CP violation could be observed at a 3σ significance for 74% of the parameter region of δ if the neutrino mass hierarchy is known and $\sin^2 2\theta_{13} > 0.03$. If the neutrino mass hierarchy is not known, the CP sensitivity is reduced to 46% of the parameter region of δ for $\sin^2 2\theta_{13} \sim 0.1$. However, in this case the neutrino mass hierarchy can be determined at a 3σ significance for 10 years of atmospheric neutrino observation for $\sin^2\theta_{23} > 0.4$.

Hyper-Kamiokande has also a high sensitivity to proton decays: longer than 1×10^{35} years for $p \rightarrow e\pi^0$; longer than 2×10^{34} years for $p \rightarrow \nu K^+$. To date, Hyper-Kamiokande is the only detector that exhibits a design with a sensitivity exceeding 10^{35} years for proton decays. Hyper-Kamiokande, thanks to its huge fiducial volume, is also able to make other observations and measurements such as precise solar neutrino observations, high-sensitive supernova neutrino observations, dark matter searches and solar flare neutrino searches.

Although the key technologies for realizing Hyper-Kamiokande have been established at Super-Kamiokande, a more realistic estimation of costs remains necessary. It is also necessary to develop low-cost, large-size photo sensors, carry out long-term stability tests of the prototype, develop technology for excavating a large volume at a low cost, and design the large-size tank and mechanical structure of the detector. The total number of readout channels of the photo-detectors exceeds 100,000, and it is essential to develop front-end electronics that can process electric signals in water. In parallel with these developments, systematic errors which limit the experimental sensitivity need to be studied by T2K, including one option of using an anti-neutrino beam.

Liquid Argon TPC

In this plan, CP violation is sought by using a 100 kton liquid argon detector located on Okinoshima island at an off-axis angle of 0.78 degree, 658 km from J-PARC.

The greatest advantage of the liquid argon detector is the capability it has to detect tracks from all charged particles at an extremely low threshold. This enables the reconstruction of the neutrino energy precisely for a wider range of the neutrino spectrum. It also helps to suppress the

[2] Here we assume 1 year = 10^7 seconds.

background events in the measurement of electron neutrino appearance. In particular, the neutral current π^0 events, one of the main backgrounds for a water Cherenkov detector, are expected to be removed efficiently by detecting the activity in the vicinity of the vertex and the different behaviour of the dE/dX at the front of the electromagnetic shower originating from electrons and photons.

CP violation is detected by accurately measuring the energy spectrum of the oscillation from muon-neutrinos to electron-neutrinos. The first oscillation peak is located at 1.2 to 1.4 GeV and the second at 0.4 GeV. While the effect of CP violation and the matter effect compete at the first peak energy, the effect of CP violation dominates at the second peak. Thus the sensitivity to CP violation can be increased by measuring the first and second peaks simultaneously using a wide band energy spectrum neutrino beam. With 8 MW×year (ten years at 750 kW) of data, CP violation can be observed at more than a 3σ significance if δ is larger than 30 degrees.

In proton decay search, high sensitivity is expected in $p\rightarrow\nu K^+$ mode since the charged kaon can be directly detected. It is therefore possible to obtain a lower limit of 6×10^{34} years for $p\rightarrow\nu K^+$ by operating the 100 kton detector for 10 years.

Necessary conditions for realization of a 100 kton liquid argon detector are as follows: 1) "demonstration of physics performances" by confirming performances for charged particle identification, energy reconstruction, and then reconstruction of neutrino interactions; 2) "demonstration of technologies" by establishing technologies for a large-size liquid argon tank, high voltage (~MV), and a purification system to realize a long drift length. Tests with a small liquid argon detector have been carried out to demonstrate the physics performance by using a beam of charged particles. Beam tests of a 400 kg liquid argon TPC detector were already performed at J-PARC using charged K, π, proton, and positron beams, and the expected performances are being verified. Key technologies necessary for realizing the detector include a large-size cryogenic container, ultra-pure liquid argon, a high-voltage generator and signal readouts. In order to establish these technologies, it is necessary to accumulate techniques by starting with a small detector and producing larger detectors step by step. While a 400-kg liquid argon TPC detector has been realized in Japan, the world's largest detector is currently 600 tons. It is planned that prototypes be produced ranging from 100 tons to 1,000 tons and to use them to measure neutrino interaction cross sections in the liquid argon to study the physics potential. The physics performance and technologies for constructing the detector should be established in the final prototype; thereafter a 100 kton detector could be constructed.

Comparison of the Two Plans

The advantage of the experiment using Hyper-Kamiokande is that the beam flux is high at the closer distance and that the CP asymmetry can be measured with high statistics. In addition, in the energy range of about 1 GeV where neutrino oscillations occur and matter effects which can cause a fake CP violation signature are small, a water Cherenkov detector displays a greater ability in identifying particles with a high detection efficiency. Meanwhile, the disadvantage is that an anti-neutrino beam with a smaller cross-section is required and that it is necessary to keep systematic errors below 5% in order to measure the CP asymmetry effect to O(10%). The advantage of the experiment using a liquid argon TPC is that background rejection is high for π^0 events and that high detection efficiency and excellent particle identification are achieved over a wide energy range, so that the CP parameter δ can be determined by an energy spectrum measurement. Meanwhile, the disadvantage is that energy of the second oscillation peak is low with a small interaction cross-section and that the detector will be smaller than Hyper-Kamiokande therefore the statistics will be decreased. Furthermore, the technologies for constructing a 100,000-ton liquid argon TPC need to be developed.

Other Domestic and Overseas Projects

In order to discover neutrino CP violation and determine the neutrino mass hierarchy through neutrino oscillations, a neutrino oscillation experiment using an accelerator neutrino beam is of prime importance. Therefore, various projects are also being studied in Europe and America. In the United States, the NOvA experiment, which has a similar sensitivity to the T2K experiment, is under construction. Further, the Long Baseline Neutrino Experiment (LBNE) project is under consideration. In LBNE, a neutrino beam is generated by a beam with a power in excess of 700 kW at Fermilab and the far detector is located at the Sanford underground laboratory in the Homestake Mine 1,300 km away. The 33 kton liquid argon TPC is the first choice for the neutrino detector, and it has excellent background rejection power over a wide energy range, excellent particle identification and high detection efficiency. A water Cherenkov detector, with a fiducial mass of 200 ktons, is the second choice, since this technology is well established even though the detection efficiency is low.

In Europe, a scenario using a conventional neutrino beam from π decays produced at CERN and observed at a distant underground laboratory is currently under consideration as the LAGUNA project. In the LAGUNA project, the following is to be considered: 1) Seven underground laboratories in Europe (the closest detector location is 130 km away from CERN, and the farthest is 2,300 km away); 2) Three detector options (water Cherenkov detector, liquid argon, and liquid scintillator). Recently a middle-sized liquid argon TPC has been proposed at 2,300 km distance and an experiment specialized in measuring the matter effect is under consideration. As a concept for the distant future, a β-beam and a neutrino factory are also being considered as an entirely new method of generating neutrino beams. In the β-beam, unstable nuclei are accelerated and circulated in a storage ring, producing the neutrino beam by beta decays of the nucleus. The Q-value of β decay is so small (MeV level) that a low-emittance neutrino beam can be produced. A neutrino factory is another idea that neutrinos from muon decays can be utilized as a beam, this method can produce a neutrino beam with a well-known energy spectrum. Currently, it is not clear whether both β beam and neutrino factory can be realized or not. An experiment for testing these principles is under way.

In parallel with the accelerator neutrino experiments, the measurements of θ_{13} by reactor anti-neutrino experiments provide important information for the CP measurement of neutrinos. By gaining precise information on the size of θ_{13} from reactor experiments the effect of CP violation can be cleanly extracted in the accelerator experiments. Especially, if θ_{13} is large (~10°), it is expected that its size can be accurately measured in reactor experiments. The Double Chooz experiment, RENO experiment, and DayaBay experiment are underway as the main reactor anti-neutrino experiments. Furthermore, the KASKA experiment is considered as a future experiment in Japan. Clearly it is important to consider a global neutrino programme of both accelerator experiments together with upgrades of the reactor anti-neutrino experiments.

4 Flavour Physics

While aiming to completely understand the physics of the electroweak energy scale as the next large milestone of elementary particle physics, the indirect search in flavour physics plays a complementary role to the direct searches for new physics at LHC. The primary goal of flavour physics is to identify tiny discrepancies in the measured observables from the standard model predictions due to quantum mechanical contributions from off-shell high mass particles; therefore, observables with small theoretical errors must be measured precisely with large statistics and well controlled systematic uncertainties. In order to obtain high statistics, either collision luminosity or beam intensity must be improved to an extreme; hence these are the experiments that explore the intensity frontier. Although the typical size of these projects is smaller, as the beam energy is lower than that of energy frontier experiments for direct searches, there are nevertheless also technical challenges associated with high intensity. Japan has been one of the leading countries in flavour physics experiments in recent years, as represented in the success of KEK B-factory. It is important that this role is preserved in the future.

There are at present some hints of new physics – namely the phenomena still consistent with the standard model within theoretical or experimental errors, which could however be concluded to be the new physics contribution in future developments – in terms of experimental results ranging from the muon g−2, B-factories and LHCb. The MEG experiment also recently drew significant interest in its search for $\mu\to e\gamma$, however, no statistically significant signal has been found to date. Also, in the case of a supersymmetry search at LHC no signatures have been found as yet. The situation will become clearer in the coming few years. Should the next energy scale be higher than expected, then the indirect search will be even more important. On the other hand, once new physics phenomena start to be observed by experiments, flavour physics will be required to identify the model of new physics by finding which observables in the new physics effect are enhanced or suppressed, and also determine the couplings of new physics. Therefore, in either case, it is advisable that the basic approach be to keep a diversity of projects and to carry out various experiments in the future. In the following subsections, individual targets of experiments (B meson, D meson, K meson, neutron, tau lepton and muon) are described.

4.1 Super B-factories

SuperKEKB/Belle II project, which succeeds KEKB/Belle, is one of the largest class of experiments of flavour physics, and covers a wide variety of targets to measure such as bottom, charm, and tau. As the largest player of the new physics search network at the intensity frontier, this must be constructed and made operational without delay.

There are several independent measurements which draw attention, all of which could show sensitivity to new physics within a few to ten years of data: understanding the difference in direct CP violation in $B\to K\pi$ for charged and neutral modes, the search for charged Higgs by measuring the branching fractions of $B\to\tau\nu$, $B\to D^{(*)}\tau\nu$ and $b\to s\gamma$, the search for new complex phases by measurement of time-dependent CP asymmetry in $b\to sqq$, the search for right handed currents by measuring time-dependent CP asymmetry in $B\to K_S\pi^0\gamma$, the search for lepton flavour violation in tau decays such as $\tau\to\mu\gamma$ and $\tau\to\mu\mu\mu$, and the understanding of the large mixing in the D^0 meson system. Detection and measurement of neutral particles (K_S, π^0, γ, ν) are especially important for those measurements, where the clean environment of a lepton collider is the key feature. The statistical uncertainty dominates the precision of most of these measurements, and therefore the expected large statistics is fairly promising. On the other hand, the precision of parameters such as the meson form factors owe much to lattice QCD calculation, for which contribution from the theory side is required. It is also important to understand the direct CP asymmetry in the D^0 meson system as reported by LHCb. Therefore, development of a theoretical calculation method for the D^0 meson system is highly desirable.

In other countries, INFN Italy has taken the lead in advancing the SuperB project. Both SuperKEKB and SuperB target high instantaneous luminosity ($8\times10^{35}cm^{-2}s^{-1}$ and $>10^{36}cm^{-2}s^{-1}$, respectively) by maximally squeezing the beam size. SuperB will realize this by digging a brand-new tunnel and SuperKEKB by reusing existing facilities. Just as in the era of KEKB and PEP-II, sound development in this field is foreseen with two projects competing for the accomplishments.

SuperKEKB will reach a milestone, namely to accumulate 50 ab^{-1} of integrated luminosity by around 2021, provided everything proceeds well. By that time, observation of various new physics phenomena or limitations on new physics are expected, however, in the case that the coupling of new physics is too small, depending on how the research develops, there may be a case for a further luminosity increase by more than a factor 10. In such an event, the feasibility of a further luminosity upgrade must be considered based on the actual experience at SuperKEKB and INFN SuperB; presently however there is no concrete idea.

There may also be the case that the centre-of-mass energy and beam energy asymmetry are altered to being more optimal for the study of tau lepton and charmed meson decays. In fact, the machine operation at the tau/charm pair creation threshold with the target luminosity of $10^{35}cm^{-2}s^{-1}$ is already included in the programme of INFN SuperB and the Super charm-tau factory at BINP. As an example, electron-positron collision with $>10^{36}cm^{-2}s^{-1}$ at $\sqrt{s}$~4.2GeV (symmetric energy) enables a search for $\tau\to\mu\gamma$ with much higher sensitivity by suppressing initial state radiation background.

4.2 Muon Physics

Discovery of the neutrino oscillation has stimulated interest in the search for lepton flavour violation also in the charged lepton sector. In the standard model with the neutrino oscillation taken into account, a charged lepton flavour violation process is highly suppressed to the level of 10^{-40} to 10^{-50}. On the other hand, if new physics exists, charged lepton flavour violation processes can be enhanced to a measurable level. Thus discovery of charged lepton flavour violation processes would be very clear evidence of new physics and experimental search for such processes should be strongly promoted.

Lepton flavour violation in tau decays probes flavour mixing between the 3rd and 2nd or 1st generations, whereas lepton flavour violation in muon decays probes the mixing between the 2nd and the 1st generations. The MEG experiment at PSI has provided the upper limit of $\mu \to e \gamma$ at 2.4×10^{-12}, and will continue to search with a sensitivity at $O(10^{-13})$. Furthermore, there is a plan to upgrade the MEG experiment to further improve the sensitivity. The atomic $\mu\to e$ conversion process is more comprehensive, and is also sensitive to non-photonic processes. In typical SUSY models, the branching fraction for $\mu\to e$ conversion is about two orders of magnitude less than that of the $\mu \to e \gamma$ decay. Therefore, both the COMET experiment at J-PARC and the mu2e experiment at Fermilab, aim at a sensitivity of $O(10^{-16})$ and have good potential for either discovering or severely constraining new physics. In order to resolve technically challenging issues, it is desirable to strengthen the organization of R&D through international cooperation and competition. As for the COMET experiment at J-PARC, the design of a new beam line and muon production target is in progress. If realized, this could become the flagship experiment of particle physics at J-PARC.

As for the muon anomalous magnetic moment, the BNL-E821 experiment measured to a 0.7 ppm precision, and claims a 3.4 σ deviation from the standard model. It is, therefore, important to verify this in new experiments with improved precision. It is also necessary to improve the accuracy for the estimation of the hadronic contribution to the vacuum polarization. At Fermilab, a new experiment using the same muon storage ring shipped from BNL is planned, aiming at a 0.1 ppm precision. At J-PARC, an experiment, based on a new technology using an ultra-cold muon beam, has been proposed, targeting a similar precision. It is therefore important to carry out an independent experiment with different systematics from the existing measurement. Further, the R&D to establish the technical feasibility should be speedily advanced.

4.3 Kaon Experiments

Since the first observation of CP violation was reported in K meson decays, Kaon experiments have made significant contributions to flavour physics for a long time. The next important target is the search for new physics through the measurements of branching fractions of $K_L \to \pi^0 \nu\nu$ and $K^+ \to \pi^+ \nu\nu$. Abroad, NA62 is being prepared at CERN, which intends to observe O(100) events of $K^+ \to \pi^+ \nu\nu$ and determine the branching fraction; a similar experiment is also proposed in the US. Simultaneously in Japan, the KOTO experiment that will measure the $K_L \to \pi^0 \nu\nu$ is under construction, this plans to make maximum use of the high power (100kW) beam intensity of J-PARC. Coupled with the charged mode, this measurement is expected to play a role in the search for new physics. It begins by updating the current upper limit (2.6×10^{-8}) obtained by the previous experiment at the KEK-PS, then proceeds by exceeding the Grossman-Nir limit (1.5×10^{-9}) and enters the sensitivity region where the new physics search is possible. In the late 2010s, KOTO will reach the branching fraction predicted by the standard model (2.4×10^{-11}). In order to go beyond the KOTO goal and search for a 10% level of deviation of new physics effects from the standard model, a new beam line must be built by extending the experimental hall, and the detector must also be significantly upgraded. The extension of the experimental hall should be studied in co-operation with the nuclear physics community.

4.4 Neutrons

For the measurement of the neutron electric dipole moment (EDM) using ultra cold neutrons (UCN), the sensitivity of a single experiment has started to reach the region of new physics predictions (current upper limit: 2.9×10^{-26} ecm, supersymmetry: 10^{-27}-10^{-28} ecm). Hence, expectations have risen for future developments. Most of the experiments being currently planned or constructed utilize accelerator-based nuclear spallation sources, and aim for sensitivities of 10^{-27} to 10^{-28} ecm. At PSI, the operation starts this year and is aiming for 5×10^{-27} ecm. At TRIUMF, an experiment which utilizes an extremely low temperature UCN source developed by KEK/RCNP is under construction. An experiment at J-PARC proposes to extract a few % of the beam from the LINAC to then be transferred to a special small extraction target. Use of an intense pulsed beam not only provides high statistics and low systematic uncertainty but also enables one to reach 10^{-27} to 10^{-28} ecm. Creating as many neutrons as possible in a short time, guiding them to the storage vessel via a newly designed magnetic convergence unit, and other such ideas show there are many innovations required and existing in key technologies. In order to gain international competitiveness, it is important that practical R&D should be promptly started and advanced from the proof-of-principle stage. Construction of facilities and beam allocation should be coordinated in a close cooperation of JAEA and KEK.

5 Non-Accelerator Particle Physics Experiments

5.1 Underground Astroparticle Physics Experiments

Introduction

Various searches for rare phenomena are pursued underground utilizing the low radioactive environment due to less cosmic ray flux and stable observational conditions. Especially, direct searches for dark matter and searches for neutrinoless double beta decays ($0\nu\beta\beta$) are vigorously pursued in international competition. In Japan, most underground projects are located at the Kamioka site initially developed for neutrino observations and now hosting a growing underground astroparticle physics community. In spite of the disadvantage of being shallower than the sites abroad, nevertheless, cooperation and effective sharing of existing research environments and resources enable the proposal of projects that achieve world class or leading sensitivity goals both cost-effectively and quickly. Continuous support is indispensable to maintaining the world's key research centre for underground astroparticle physics.

Currently, the sizes of individual projects are not huge and a variety of key methods coexist. It is important to keep the diversity for the moment, but at the same time it is also important to share scientific directions in the field so that a large-scale cooperative project can be quickly and efficiently launched upon a new discovery. Researchers of underground experiments either belong to the high energy, cosmic ray or nuclear physics communities and in order to cover large important areas of research, these communities need to cooperate to achieve the appropriate evaluation, promotion and support for projects.

Dark Matter Search

Recent developments in cosmological observations have definitely established the existence of dark matter beyond the known matter particles. Hypothetically argued, mass and interaction cross sections of the dark matter particle range over tens of orders of magnitude among the various hypotheses. Among possible candidates for dark matter particles are, weakly interacting massive particles (WIMPs) predicted by supersymmetric models and which have attracted considerable attention and been the goal of vigorous international research, aiming at a direct observation of WIMPs.

While the DAMA/LIBRA experiments using NaI crystal reported an 8.9 sigma significant seasonal variation in their signal rate, in correlation with the Earth's orbital eccentricity, as evidence of dark matter, other observations using different experimental techniques are providing inconsistent results, so making the matter still very controversial. The experiments refuting the DAMA/LIBRA results have much better sensitivities for WIMPs with masses of around 50GeV. However, in these measurements of very low energy nuclear recoil, ionization in the media and quenching effects of scintillation light may still cause ambiguity. Moreover, several reports of possible indications of low mass WIMPs around 10GeV have further complicated the situation.

For discovery of SUSY WIMPs, it is important to improve the sensitivity to the cross section at around 50GeV from the current 10^{-44}cm^2 level to 10^{-46}cm^2 level. To achieve this sensitivity, realization of a large detector with about 1 ton effective mass is necessary. Since discovery is the primary target, it is advisable to advance a scalable project such as XMASS1.5. If a signal is detected, the next step would be to gain further confirmation and to explore the physics behind it. In addition to high statistics measurements of the recoil spectrum and seasonal variation measured with a large-scale detector such as XMASS2 with a 10 ton effective mass, measurements with different nuclei and different techniques, measurements of the direction of dark matter motion with TPCs (NEWAGE) or emulsion techniques, and measurements of spin dependence and inelastic scatterings will become important. These diverse investigations should be advanced in parallel. On the other hand, verification of the controversial 8.9 sigma signal of DAMA/LIBRA by using the same detector technology (NaI) is necessary. Under the existing circumstances where no signal of supersymmetry has been observed by LHC, searches over a wider parameter region of theories and for other types of dark matter particles, such as axions should also be pursued without theoretical prejudice.

Search for 0νββ

Searches for 0νββ decay are currently the only realistic way to investigate the Majorana nature of neutrinos. Discovery of 0νββ would be clear evidence of Majorana neutrinos and lepton number violation, irrespective of what kind of physics causes it. Since the decay rate is proportional to the square of the effective Majorana mass, absolute neutrino masses may be determined. While an accuracy of approximately 200 meV is aimed for by a project to measure the absolute neutrino mass from a beta decay spectra, cosmological measurements are expected to reach a sensitivity of 50 meV or ultimately 20 meV. The effective Majorana neutrino mass has been evaluated by the studies of neutrino oscillations to be more than 60 meV for the case of degenerate neutrino masses, 20 to 60 meV for an inverted mass hierarchy, and less than 20 meV for the normal mass hierarchy case. These mass regions set the milestones for future searches. A 6 sigma signal of 0νββ decay at the effective mass of about 320 meV has been claimed by a high resolution measurement using ^{76}Ge (KKDC claim) and awaits further verification, since multiple background candidates are already known.

Current ongoing projects initially target a sensitivity of approximately 60meV to verify the KKDC claim and the degenerated mass region, and also consider future extendability to 10~20 meV to explore the inverted mass hierarchy. Thus 0νββ searches are expected to lead the way in the pursuit of absolute neutrino masses measurements in the future. If the absolute neutrino mass is determined by beta decay spectra measurements or by cosmological observations, or if the neutrino mass hierarchy is determined by the neutrino oscillation measurements, comparisons with measurements of 0νββ decay could enable the determination of the Majorana CP phases, to refute the Majorana nature, and to possibly identify physics models behind the neutrino masses.

In order to cover the inverted mass hierarchy, about 1 ton of double beta decay nuclei would be necessary, and realization of such a huge detector with low radioactive background is the main issue. This issue is shared by neutrino detectors and thus applying an existing neutrino detector to 0νββ searches would be effective, just as KamLAND-Zen is based on the neutrino detector KamLAND with a ^{136}Xe source, also from the point of view of extendability. These detectors have the merit of having more general purposes other than only 0νββ searches even if no signal of 0νββ is found. If however, 0νββ decay is discovered, verification using different nuclei and different methods would be necessary to resolve the uncertainties of nuclear matrix elements and the difficulty of eliminating unidentified backgrounds, and also to identify the new physics behind 0νββ decay. Diverse R&D on particle identification techniques for rejection of unexpected backgrounds, or detectors capable of measuring angular distributions and general devices applicable to various nuclei are indispensable.

In Japan, several groups are advancing independent projects employing technologies of their own originality and/or expertise. The CANDLES experiment using ^{48}Ca has a good tolerance to background thanks to its highest Q-value but an isotopic enrichment is an important remaining issue in overcoming its low natural abundance of 0.2%. Also developments of drift chambers and emulsions which are capable of measuring angular distributions and multiple nuclei are underway but need to be speeded up to become internationally competitive.

Although it is difficult to foresee science more than 5 years into the future, it is apparent that future projects need to be large-scale and advance planning is important. If a new large-scale neutrino detector is realized, Super-Kamiokande, for example, can be effectively converted into a detector for dark matter or for $0\nu\beta\beta$. There is a proposal for Super-KamLAND-Zen which combines Super-Kamiokande and liquid scintillator to reach a $0\nu\beta\beta$ sensitivity of the normal mass hierarchy.

5.2 Cosmological Observations

Introduction

Recently, cosmological observations have become ever more important to elementary particle physics. It is expected that experimental projects in cosmology will become more actively promoted while keeping in good balance with accelerator-based projects as well as cooperating with closely related research fields. In particular, the quests for understanding cosmic inflation and dark energy are two important topics that require cosmological observations as their main tools; observations of CMB polarization for testing inflation and studies of dark energy with the Subaru telescope are in progress. Both of these observations are also very sensitive to the sum of neutrino masses. It is expected that each method alone will eventually reach a sensitivity below 100 meV. This would be a significant milestone as a sensitivity at this level corresponds to the lower limit for the inverted mass hierarchy.

Verification of Cosmic Inflation with Cosmic Microwave Background (CMB)

Discovery of the B-mode polarization of the Cosmic Microwave Background (CMB) would be direct evidence for cosmic inflation. It would also provide information about the energy scale of cosmic inflation. The search for the B-mode polarization caused by inflationary gravitational waves is also important as it provides a unique window on super high energy physics that cannot be directly accessed with accelerator based research.

The Japanese CMB group plays a key role in the international collaborations QUIET and POLAREAR. QUIET has already published its initial result one that is one of the most precise measurements of the CMB polarization to date. POLARBEAR was deployed in the Chilean Atacama desert and started observations in 2012. An advantage of POLARBEAR is its large primary mirror and ability to observe a large fraction of the sky. Projects that compete with POLARBEAR include BICEP2/KECK, which are deployed at the South Pole. The experimental sensitivities of these projects will exceed the sensitivity of the Planck satellite. One key discovery is expected in 5 years if the tensor-to-scalar ratio is around 0.01 or larger. POLARBEAR plans to deploy more telescopes in the future and measurements with these multiple telescopes will be complementary to the observations of the satellite described below.

There are several studies on future satellite observations which aim to achieve even higher sensitivities. The mission of such satellite projects will be to search for the tensor-to-scalar ratio down to around 0.001 by observing the whole sky without atmospheric fluctuations. This would allow us to test representative inflationary models in more detail. Even if a discovery is made by POLARBEAR or any other competing project before such a satellite is launched, the high precision B-mode measurements with a satellite would be important in narrowing down cosmological models. In Japan a feasibility study for the satellite named LiteBIRD, which is planned for launch around 2020, is in progress. Major future satellite projects in Europe and the US propose the launching of relatively large satellites which may take a long time. The LiteBIRD satellite, in contrast, is small but sufficiently sensitive and able to focus on the tensor-to-scalar ratio measurement and hence earlier observations and discoveries might be possible. Collaborative studies of an international working group formed at JAXA have been in progress with participants including high energy physicists, astronomers, superconducting device engineers, and cosmologists. We expect that this activity will develop creating a good balance between independence and international cooperation.

Investigation of Dark Energy

A surprising discovery was made at the end of 20th century namely that of an accelerating expansion of the universe as indicated by supernova data. The Physical model behind the accelerating expansion is not yet known, and the unknown source that is responsible for the acceleration is called dark energy. In order to understand the essence of dark energy, it is important at this stage to improve the precision of observations to see if the equation of state evolves as a function of the cosmological scale. To this end, we should improve our understanding of the cosmic composition (what existed in the universe, as well as when, where, and how). Type-Ia supernovae, galaxy distributions, weak lensing and baryon acoustic oscillations are to be studied in future dark energy observation projects.

SuMIRe is the next-generation dark energy project in Japan, which is an upgrade of the Subaru telescope for imaging and spectroscopy. The Hyper Suprime Cam (HSC), which has been constructed for weak lensing surveys with imaging, is scheduled to be deployed in 2012. With 900 million CCD pixels in the focal plane, the HSC will perform large-area surveys to detect billions of galaxies, investigate 2D distributions of dark matter from weak lensing analyses and obtain improved knowledge about the history of the cosmic expansion and dark energy. Another instrument is the Prime Focus Spectrograph (PFS), which is a new spectrometer to be installed around 2016. The PFS will cover 2000 deg^2 and measure redshifts of more than a million galaxies. We expect that the spatial information from the HSC and the redshift (i.e. time) information from the PFS will show large synergies. SuMIRe will also allow the testing of cosmic inflation from measurements of non-Gaussianity, test general relativity on a long distance scale, and determine the 3D distribution of dark matter.

The SuMIRe project will be more sensitive than any other ground-based proposal and thus be quite competitive. Its goal is to reveal new and decisive knowledge on the nature of dark energy before the observation with a new satellite (such as Euclid) starts around 2020.

6 Human Resources and Development of Technology

In high energy physics experiments physicists aim to achieve the world's best results by combining various cutting-edge technologies. The high energy physics experiments are consequently full of forefront technologies and are thus a fascinating research field for young researchers especially from the viewpoint of technology. Continuous development of technology and the training of young researchers who support it are essential for this field of research to continue developing. Several problems concerning human resources and technological developments have arisen recently.

- Length of cycles of experiments: high energy physics experiments become larger and take a longer time. It is difficult for even a competent student or young researcher to experience the whole process of the experiment from project design, R&D and construction of detectors, commissioning and operation, to data collection and physics analysis. More and more young researchers miss opportunities to work on technological developments and it could prevent smooth inheritance of technology.
- Specialization and subdivision of technology: there are many driving force technologies in high energy physics, such as accelerator technology, detector technology, electronics, superconducting technology, mechanical engineering, etc. These cutting-edge technologies have become more and more specialized and subdivided in recent years, and it is difficult for individuals to obtain a broad experience of the various technologies used in the present high energy physics experiments. This also causes difficulties in exchange of human resources among subdivided fields of expertise.
- Lack of resources: because of the decline of the economy and the pressure for short term outcomes, the budget for basic research is suffering from a significant reduction. This leads to the closure of electronics workshops at universities, a decrease of technical support staff at universities and laboratories, etc., resulting in the deterioration of the research environment for developing cutting-edge technologies and causes difficulty in technological inheritance also due to the mass retirement of the baby-boom generation.

Active exchanges of human resources at various levels are important in order to mitigate the above problems. Further efforts to increase the interchanges of personnel between projects and institutes will be necessary. Providing young researchers with opportunities to work on small/ medium size experiments at the beginning of their careers as researchers, and employment of young researchers inclined toward challenging cutting-edge technologies may be effective here. Also necessary measures should be seriously considered and undertaken to help to continuously develop forefront technologies and train young researchers who will support the technologies in the future. Future large-scale projects cannot be realized without the technological development and the existence of sufficient human resources.