

1. Preamble

The Roadmap (five-year plan) of the High Energy Accelerator Research Organization (KEK) is the laboratory's mid-range research plan; the previous version was published in December 2007, and supplemented in April, 2010. This new "KEK Roadmap 2013" is a major revision that was prepared by KEK's Research Steering Committee through its deliberations since April 2012.

Particle accelerators support a wide range of scientific research, including exploration of the ultimate structure of the material world, as spearheaded by particle and nuclear physics, which probe into the origin of the universe. The research platform provided by particle accelerators also propels material science, life science, and medicine, and helps address energy issues. KEK is an inter-university research institute corporation that is mandated to support basic research in particle physics, nuclear physics, material science, and life science by utilizing particle accelerators. To accomplish this mission, KEK has been engaged in the development, construction, and operation of cutting-edge particle accelerators and thus has also been serving as a major center of excellence for accelerator sciences in Japan and in the world. The goal of this new Roadmap is to further augment the core competencies and roles of KEK so as to continually produce world-leading, top-notch scientific results.

In producing this Roadmap 2013, KEK's Research Steering Committee solicited input through the Institute of Particle and Nuclear Studies (IPNS) and Institute of Materials Structure Science (IMSS) from members of the relevant research communities in particle physics, nuclear physics, and material and life science at the photon factories and neutron and muon facilities, along with scientists' future research plans therein. In August 2012, an interim report was made available to these community members for review and additional comments. This input was collected and fed into further deliberations by the Research Steering Committee, which converged into Roadmap 2013. Thereafter, further deliberations were held regarding photon science (synchrotron radiation research). These were reflected in major revisions in June 2016.

The first part of Roadmap 2013 discusses the roles of KEK with respect to long-range issues in the relevant scientific fields, i.e., particle physics and nuclear physics, material and life science, the advancement of particle accelerators and applied research, the development of detector-related technologies, international cooperation, the development of human resources, and the laboratory's relationship with society at large. The second part deals with the five-year research strategy for KEK, starting in the year 2014, as formulated by the Research Steering Committee on six topics, which are summarized briefly below:

- Japan Proton Accelerator Research Complex (J-PARC)
At the neutrino facility, a significant improvement in the measurement precision of the T2K experiment will be pursued. In addition, new research plans will be developed for the next generation of long-baseline neutrino oscillation experiments, while relevant preparatory studies are pushed forward in parallel.

In research activities at the Hadron Experimental Facility, experiments at the present and new primary proton beam lines will be steadily advanced, while additional efforts will be made

toward future extension of the facility.

In the neutron program, the high-priority task is to meet the initial performance goal of the pulsed neutron experimental facility; this will require further development, construction, and improvement so as to realize great strides in material and life science.

In the muon program, the muon beam lines will be completed and continuously improved. This will support research in material and life science through sophisticated and creative muon spin rotation, relaxation, and resonance (μ SR) experiments, a wide range of applied research, and research in fundamental physics.

Regarding the program for improving J-PARC's accelerator systems, a high-priority item is to rapidly meet the design beam intensity goal, to be supplemented soon thereafter with preparation for the next-stage upgrade plans for the facility, which will enable a major increase in the beam intensity.

- SuperKEKB/Belle II
The goal at SuperKEKB/Belle II is to complete the construction of the accelerator and detector facilities, and then to achieve the design luminosity performance on schedule and to initiate in-depth exploration of new physics.
- Large Hadron Collider (LHC)/ATLAS
The main agenda at LHC/ATLAS is to continually participate in the experiment and to take a proactive initiative in upgrade programs within the international collaboration at both the accelerator and detector facilities.
- International Linear Collider (ILC)
KEK will play a central role in creating an international preparatory group and will lead the effort on advanced R&D, the engineering design of the apparatus and facility, and the organizational design toward groundbreaking for the linear collider project to be hosted in Japan, within the framework of a global collaboration.
- Photon Science (Synchrotron Radiation Research)
KEK will ensure continued stable operation of the Photon Factory (PF) and Photon Factory Advanced Ring (PF-AR) to advance studies in photon science. In addition, KEK will draw up specific plans for a 3 GeV-class storage ring-type high-brilliance synchrotron light source as quickly as possible, and will work with related institutions toward its early realization.
- New development of accelerator and detector technologies
KEK will contribute its expert knowledge and technical capabilities with respect to particle accelerators and detectors to collaboration with scientists from research fields of overlapping interest and to numerous industrial and medical applications for the benefit of society. KEK will also promote research that has the potential to significantly expand accelerator and detector technologies in the long term.

As stated earlier, Roadmap 2013 outlines the research programs to be pursued at KEK and is the result of input from many members of the relevant scientific communities. Timely realization of the programs enumerated here requires unfaltering execution of plans that are conceived and continually optimized with shared understanding of the development of the relevant science and technologies, as well as accurate and objective understanding of the availability of human and financial resources. In particular, the pursuit of the long-range projects has to be followed through

via periodic reviews with respect to clearly defined mid-term goals, as noted and appropriate.

2. Long-Term Prospects and KEK's Role in Each Research Area

2.1 Particle and Nuclear Physics

Prospects for Particle and Nuclear Physics Research

Research in the past several decades using particle accelerators and other tools has revealed the properties of various nuclei and elementary particles that constitute the materials surrounding us. We are now getting a glimpse of the fundamental laws of nature as well as a picture of the primordial Universe. Recent experiments at the LHC of the European Organization for Nuclear Research (CERN) discovered a candidate particle for the Higgs boson, which has been sought for decades. The most urgent task at this moment is to follow up on this discovery, understand the mechanism of electroweak gauge symmetry breaking, and uncover the new physical laws behind it. Recent cosmological observations indicate the existence of dark matter and dark energy, which in turn also strongly suggest the need for new laws of physics. Some of them are anticipated to emerge in experiments at the energy frontier.

Flavor physics, on the other hand, is poised to illuminate the properties of particles, such as CP violation, that cannot be fully unraveled by accelerators at the energy frontier. New family structures or new types of CP violation, as naturally expected from new physical laws, have not yet been observed. This means that the new physical laws possess a built-in mechanism for suppressing arbitrarily large flavor transitions or CP violation. Future high-precision studies are strongly expected to elucidate this issue. In reactor experiments and long-baseline experiments with particle accelerators, neutrino oscillation phenomena have been confirmed, and the first measurement results for the mixing angle θ_{13} have become available. This opens a path to the discovery of CP non-conservation in the lepton sector, on which proposals for next-generation experiments are under discussion worldwide.

An important subject in nuclear physics is the improvement of our understanding of various many-body quark systems on the basis of quantum chromodynamics (QCD). The standard scenario for the birth of the Universe starts with the Big Bang, followed by a high-temperature quark–gluon plasma state, which subsequently yielded hadrons as the expanding Universe cooled, leading to the creation of light nuclei and later of heavy elements in supernova explosions. However, the characteristics of each of the material phases and their transition mechanisms are yet to be fully understood and currently remain as open issues to be resolved.

Particle and Nuclear Physics Research at KEK

The realization of a linear collider with a center-of-mass energy of about 500 GeV is the next future project that is strongly desired by high-energy physicists worldwide, who seek to obtain a full understanding of the Higgs boson and to fully unravel the new physical laws that are expected to emerge at the LHC in the near future. Many scientists in Japan have been playing key roles in the R&D toward the ILC, and are intensifying their efforts where KEK is expected to take a lead. Such efforts should come in parallel with participation in LHC experiments that pursue more detailed studies of the properties of the Higgs boson and a direct search for new particles.

KEK has been advancing research in flavor physics at KEKB (B factory) and at J-PARC, the latter of which is a joint project with the Japan Atomic Energy Agency (JAEA). The Belle experiment has

achieved impressive scientific results on the basis of the world's highest luminosity attained at KEKB as an electron–positron collider. This particle accelerator is now undergoing a major upgrade into SuperKEKB with a 40-fold increase in luminosity. The Belle II experiment is scheduled to begin operation following the startup of accelerator commissioning in JFY2014, and it will examine the decay of B mesons and τ leptons with an unprecedented precision. A variety of experiments on flavor physics are in preparation for J-PARC on subjects such as K^0 rare decays, muon–electron conversion phenomena, and the anomalous magnetic moment of the muon, all of which use high-intensity proton beams. Measurement of the neutron dipole moment is another important subject, for which experimental schemes with beam lines at TRIUMF and J-PARC are being examined. All these experiments search for new physics in phenomena that are difficult to observe in experiments at the energy frontier. Depending on the outcome, they could significantly affect the future direction of particle physics.

The T2K neutrino experiment aims to make high-precision measurements of the mixing matrix elements in the lepton sector using the high-intensity beam from the J-PARC main ring (MR). The off-diagonal elements of the mixing matrix are responsible for neutrino oscillation, and the complex phase angle, if non-zero, will give rise to CP violation in the lepton sector. In parallel to these efforts, next-stage research strategies have to be formulated regarding how to address the mass hierarchy issue, where to directly observe CP non-conservation, and other issues. The field of neutrino research is a highly competitive one in which measurements at nuclear reactors play a major role in addition to those at particle accelerators. Domestic research programs have to be planned with this context in mind.

Nuclear physics and hadron physics are a major research theme at J-PARC's Hadron Experimental Facility. Its focus is on understanding the hadron structure, nucleon–nucleon interactions, and properties of high-density nuclear matter in a unified fashion on the basis of QCD. The ultimate goal here is to draw the entire picture of the evolution of the Universe and matter by understanding nucleosynthesis in the primordial Universe and during supernova explosions. Toward this goal, a diverse set of experimental programs should proceed in parallel. One such program (KISS) involves studies of unstable nuclei in the context of nucleosynthesis, which is conducted as a joint project of KEK and RIKEN.

By applying the technologies developed in studies at particle accelerators, KEK has been making significant contributions to the execution of non-accelerator experiments as well. Although experimental research at particle accelerators constitutes the primary effort at KEK, the laboratory will maintain the possibility of active engagement in non-accelerator experiments, as suitable contexts are acknowledged in particle physics, nuclear physics, and related research fields.

Theoretical studies in parallel to experimental research are another important constituent of basic science. Although experiments in many cases examine the validity of theoretical models of nature, theoretical studies attempt to build and refine such models on the basis of experimental observations. Even in superstring theory, which deals with an energy scale far beyond the reach of current experiments, possibilities exist for tracing its signature in observations of the evolution of the Universe. In addition, an accurate interpretation of complex experimental data sometimes requires close collaboration with theorists. In this regard, direct collaboration between experimental and theoretical scientists is essential for extracting the maximum outcome from experiments at J-PARC. Theoretical studies are widely pursued in particle physics and nuclear physics worldwide. Active participation in theoretical studies is an important part of the mission of KEK as the leading strong organization in this area in Japan.

Computational research in theoretical studies in particle and nuclear physics requires large-scale

supercomputer infrastructure, and KEK, as an Inter-University Research Institute Corporation, has been serving as a leading host institution. In the area of lattice QCD studies, which is the most demanding in terms of computational power, results are emerging that successfully reproduce realistic QCD phenomena. High-precision calculations of the form factors of hadrons, which are required in data analysis at SuperKEKB/Belle II, and first-principle calculations of the forces between baryons will be critical in complementing or assisting efforts to understand experimental data. KEK will advance computational research in particle and nuclear physics for its theoretical value as well as in ways coherent with the evolution of experimental studies.

2.2 Material and Life Science

Prospects for Material and Life Science Research

The mandate for material and life science research is to understand the functionality and diversity of the matter that surrounds us in terms of fundamental principles, thus helping us update our view of the material world, and eventually enriching our ability to produce useful new materials. Increasing emphasis has been placed recently on materials that provide functionality for a sustainable society, as exemplified by the concept of “green materials.” The challenge that material and life scientists face is to find ways to integrate the basic principles and concepts in the laws of the material world with the useful functionality sought by society. Research in material and life science aims to create pathways for understanding the diversity of materials, identifying the principles underlying their diversity, discovering the mechanism by which their functionalities emerge, and forging ways to produce materials with useful functionality for us. The functionality of materials is strongly influenced by the cohesiveness, interaction, and hierarchical nature of the electrons, atoms, and molecules that comprise them. Quantum beams are recognized as increasingly important probes to use here because they allow us to examine materials having vastly varying structural length scales and characteristic time frames by using many types of structural analyses and spectroscopic methods. In particular, combined, coordinated use of various quantum beams is proving to be indispensable for understanding diverse materials and multifaceted biological phenomena.

Material and Life Science Research at KEK

KEK’s IMSS is an inter-university research institute. Its mission is to conduct advanced studies in diverse fields of material and life science by providing community members with its research infrastructure, while supporting and promoting the human resource development necessary for the relevant research fields.

The IMSS provides a set of multiple quantum beams (SR, neutron, muon, and slow positron) as research tools within a single organization. This capability is unique among similar institutes worldwide. The IMSS continually improves its beam lines and research infrastructure, and promotes cutting-edge research so as to support research by creative minds from diverse scientific communities and to invigorate their research fields. In particular, the Condensed Matter Research Center (CMRC) and the Structural Biology Research Center (SBRC) are two tiers within IMSS in which strategies for integrated, coordinated exploitation of quantum beams are developed and executed. The IMSS instrument R&D team will take the lead in developing instrumentation technologies relevant to the IMSS by closely coordinating its efforts with those at the Detector Technology Project Office of the Department of Advanced Accelerator Technologies in order to advance the technologies supporting experiments with quantum beams.

The IMSS will adopt “Hydrogen and Spin in Matter” as its key phrase for the next five years to

articulate its emphasis on integrated, coordinated use of various quantum beams and to stress its service as a stimulus for scientific research in much wider fields beyond hydrogen and spin. Specifically, a focused technical effort will be made to improve the sensitivity and precision of the equipment at research platforms with various quantum beams for studies of hydrogen and spin in matter and for better understanding of these studies.

Hydrogen atoms are found in almost all organic and biological materials in different forms. Their behaviors are directly linked to the characteristic functions of the materials that contain them. In inorganic materials, the ability of hydrogen atoms to store energy and the peculiar characteristics arising from their quantum behavior are of great interest. In addition, the spin states of hydrogen are deeply relevant to the functionality of biological materials, as well as to magnetism in general.

“Hydrogen and Spin in Matter” poses a challenge to SR facilities because the interactions of photons with hydrogen and spin are not strong. However, hydrogen and spin are expected to grow into one of the major subject areas of synchrotron x-ray research in the near future. In anticipation of “Hydrogen and Spin” and scientific advances beyond, KEK is therefore pursuing plans to build a 3 GeV-class storage ring-type high-brilliance light source. Although the neutron is known to be highly sensitive to hydrogen and spin, quantitative studies with neutron beams face unresolved issues such as the high background due to incoherent scattering of hydrogen nuclear spins and the recoil effect of hydrogen atoms. In addition, strict separation of magnetic scattering and nuclear scattering of neutrons necessitates spin polarization analysis in polarized neutron scattering. However, no technology currently exists for analyzing neutron polarization that can be applied across a wide range of neutron energies. The muon is highly sensitive to local spin states within materials. It also behaves as a light isotope of hydrogen; therefore, it is expected to serve as a unique probe for the electronic states of captured or doped hydrogen, which are strongly linked to functionality in the context of material and life science. These aspects are very difficult to decipher with probes other than muons. A positron injected into matter will yield information on the charge density at the location where it annihilates with an electron. This allows studies of the expansion of the lattice induced by hydrogen and local structural changes such as atomic vacancies or structural defects that selectively capture hydrogen. A new challenge is to learn how to obtain information on hydrogen and spin by taking advantage of the sensitivity of the positron on the surfaces of condensed matter.

The CMRC and SBRC in the IMSS at KEK will take the initiative in bottom-up efforts in basic research in the context of Hydrogen and Spin in Matter, as well as in developing relevant beam control technologies and methods in instrumentation and analysis. At the same time, the CMRC and SBRC will lead the effort in research programs with a specific top-down agenda. In the next 5–10 years, the CMRC will be engaged in the Elements Strategy Initiative, with an emphasis on materials for electronics and magnetic applications. The SBRC will participate in the Platform for Drug Discovery, Informatics, and Structural Life Science with the theme of “From analyzing structure to using structure” by using various quantum beams in an integrated, coordinated manner.

Quantum Beam Platform Complex for Material and Life Science at KEK

KEK aims to establish an international center of excellence with a quantum beam platform complex at the IMSS within approximately the next 10 years. In addition, with this platform complex, KEK will facilitate human resource development in the areas of material and life science by encouraging partnerships with universities. The long-term perspectives for the quantum beam platforms in this context at the IMSS are outlined as follows.

SR has become an indispensable tool in a wide range of disciplines including physics, chemistry,

materials science, life sciences, and earth and planetary sciences. The reason is its ability to precisely determine the crystal structures and electron states of materials. Today this ability applies not just to static structures and electron states but to their evolution over time. KEK will continue at the forefront of advancing photon science, while supporting research in a wide range of disciplines that use SR. To these ends, KEK will move quickly to build a new 3 GeV-class storage ring-type high-brilliance light source and begin its operation. The high-brilliance, high-coherence SR to be produced by this light source ranges from vacuum-ultraviolet and soft X-rays to hard X-rays. Use of this SR will make it possible to determine local crystal structures and electron states with nanometer-scale spatial resolution and meV-level energy resolution. The studies will thereby enable understanding of the mechanisms of functional expression in nano-scale heterogeneous systems, which often play an important role in functional materials. A particular aim will be to clarify the structures and electron states specific to interfaces between different phases or materials that inevitably occur in heterogeneous systems. This will be a major breakthrough in the search for the origin of functions.

The neutron probes the atomic lattice, spin structures, and electron states of matter. It has a superior penetration power into materials, although it tends to be lower in brilliance and beam flux than SR. The Neutron Science Laboratory at KEK (KENS) aims to develop techniques for controlling the neutron spin and for producing spatially focused neutron beams, approximately one micron in diameter, within the next 10 years. The method of using a magnetic field gradient increases both the beam density and spin polarization. Realization of the world's most brilliant polarized neutron beam is anticipated as an outcome. Such polarized neutron beams will allow us to freely choose the probing location from a material's surface into the bulk, making it possible to quantitatively compare the data with information obtained using other types of quantum beams such as SR. Furthermore, KENS will try to realize inelastic neutron scattering experiments with 10 eV neutrons (the world's highest energy) by pressing the limit of spallation neutrons, thereby tackling research on high-speed dynamics with Brillouin scattering and other techniques. Such technical development will allow us to begin the next generation of material and life science research on subjects including the near-surface dynamics, structural analysis of micromaterials, and observation of charge excitation.

The construction of a second neutron target station at J-PARC is being contemplated for this same period. If the two are combined, they will offer opportunities to rapidly mature the experimental methods using new devices, which in turn are expected to induce the creation of new techniques. KEK will lead the efforts in both the cutting-edge and generic uses of neutron beams, which span the range from basic research to industrial applications related to material and life science.

Techniques involving μ SR are in good contrast with those using SR or neutrons, which approach the structures of materials and their fluctuations in terms of wavenumber–energy space. Muon probes are uniquely capable of providing scientists with local information in matter, which is unavailable otherwise and is highly complementary to data from other probes. The major goal of material science using muons in the next quarter-century will be to bring this technique to a sufficient level of sophistication and maturity, which then would allow us to visualize what has so far remained invisible. To achieve this goal, KEK will bring its muon facility to good condition, with the world's highest beam intensity, in particular, in the form of an ultra-slow muon beam with variable energy, while expanding its user base. KEK will establish a unique “microscopic” evaluation methodology for unraveling the atomic origin of surface or interface phenomena (roughly a few nanometers). The high beam intensity that is available at J-PARC is expected to enable measurements with a sensitivity and precision superior to those attainable with conventional slow muons. With these prospects in mind, KEK will make the muon beam infrastructure available to a wider range of material research, including industry applications and soft matter or life science materials, in

addition to basic science. Finally, KEK will support high-precision measurements of the basic properties of muons and contribute to research in fundamental physics.

In the area of research with slow positrons, KEK will take full advantage of its infrastructure at the accelerator facility, prepare a world-class slow-positron beam line, and establish a method of surface structure analysis that employs positron diffraction techniques. In addition, KEK will spearhead the development of a high-intensity polarized positron beam. KEK will use these R&D efforts to promote the expansion of a new user community that uses slow positrons as a tool in material and life science.

2.3 Development of Particle Accelerators and Related Technologies at KEK

State-of-the-art particle accelerators are the primary tool with which KEK has been exploring the fundamental principles of the material world. KEK will continue to lead the development of new particle accelerators and a wide range of their applications within and outside of Japan, on the basis of its real-life experiences obtained in the design, development, construction, operation, and performance improvement of particle accelerators. Basic scientific research in the next generation will require solid, high-performance particle accelerators and their support infrastructure. KEK will exploit new technologies as outlined below, produce quantum beams with parameters in the new regime suitable for future scientific goals, and contribute to creative endeavor in the experimental sciences. KEK will also monitor new ideas and technical innovations, actively advance them in practical applications, and return their benefits to society at large.

RF technology: Superconducting cavity technology, the practical implementation of which was pioneered by TRISTAN at KEK, is now in common use, including new applications at BEPC II (Beijing) and NSRRC (Hsinchu). KEK is currently conducting in-house studies of mass production techniques for superconducting cavities for the ILC. Assembly of copper RF cavities by electroforming is another technique that originated at KEK and is now widely used worldwide. Cavities loaded with magnetic alloy and crab cavities, which have been in operation at J-PARC and KEKB, respectively, are on their way to being adopted at the LHC and elsewhere. The demanding specifications at KEK in the past have yielded unique and creative solutions such as ARES cavities at KEKB, ACS cavities at J-PARC, and damped cavities at the PF and Accelerator Test Facility (ATF), all of which turned out to be keys to the success of the respective accelerator systems. KEK will continue in this tradition and keep advancing RF technologies for future accelerators such as the ILC. Another important frontier is the improvement of the systems for the generation, transfer, and control of high-power RF, which KEK will address by developing advanced digital RF controls and semiconductor devices.

Magnet systems: The frontier studies of particle physics at the SuperKEKB, muon $g-2$, and $\mu-e$ conversion (COMET) experiments require superconducting magnets with ultrahigh-precision three-dimensional designs. They are pursued in conjunction with a nanometer-level three-dimensional beam dynamics analysis. While meeting these demands, KEK will also contribute to the LHC upgrade program by advancing its superconducting magnet technologies, which KEK has supported through construction of the neutrino beam line at J-PARC and the initial implementation of the LHC. Pulsed magnets and their drivers in use at J-PARC, the electron/positron injector, SuperKEKB, the PF/PF-AR, and the ATF are being pushed to the limit of ultimate performance with a variety of creative ideas introduced to realize their long-term, stable operation. KEK will continue building up its comprehensive knowledge base, which allows the laboratory to respond to challenges in magnet system design, including the need for high-precision power supplies, high-precision alignment, resilience against radiation, and improved power efficiency.

Beam sources and vacuum systems: The performance of beam sources is becoming an increasingly

decisive factor in the success of accelerator projects such as J-PARC, SuperKEKB, and the ILC. KEK will pursue both its in-house development efforts and collaborations with institutions within and outside of Japan as well as with colleagues from other fields. The development of related technologies such as lasers is another research focus. The vacuum systems in particle accelerators have to withstand demanding operational conditions under strong electromagnetic fields, heating, discharges, and exposure to lost beam particles and electron clouds, which are created by the passage of high-current beams. KEK has accumulated experience in the development, design, and operation of various vacuum system components at the high-current storage ring KEKB and of a large-scale ceramic beam pipe system at J-PARC. KEK will strive to advance the development of components for use in ultralow-vacuum systems at next-stage particle accelerators, while acquiring and absorbing a deeper understanding of related areas of surface physics and material science.

KEK has been accumulating a large amount of diverse experience and expertise on high-speed, high-precisions beam instrumentation devices. KEK will maintain its own creative efforts as well as critical learning of the methods and techniques that are rapidly being developed at new accelerators worldwide. Dynamic integration of evolving beam instrumentation techniques and a system framework with EPICS will allow KEK to maintain its competitiveness in the field of general-purpose and forward-looking accelerator control systems. With the combined development of accelerator control systems and numerous safety systems, KEK will also pursue possible spin-off applications to other fields such as particle detectors.

KEK will establish the latest component technologies, as discussed above, for use in future accelerators within and outside of Japan. The ATF and Superconducting RF Test Facility (STF) are important vehicles for performing these tasks in the context of both the technology and international collaboration.

Accelerator theory: KEK has been making a number of ground-breaking contributions to theories of particle accelerators and beam dynamics. KEK will continue its effort to develop and spread advanced methodologies for accelerator design and computer codes. In new particle accelerators, the beam diagnostics and control technologies must be tightly meshed with advanced accelerator theories and design considerations; this allows new beam dynamics concepts to be readily tried out in a short turn-around time at the actual operational settings for the most efficient performance improvement. KEK will lead this arduous long-range endeavor, which is shared by accelerator laboratories worldwide.

Radiation protection: KEK will continue to advance techniques for measuring and simulating the mixed stray radiation and radioactivity that occur during the operation of particle accelerators. KEK will combine these techniques with countermeasures against radio-activation of the air and water around accelerators and integrate them into an advanced methodology for safety system designs at next-stage accelerators. In addition, KEK will improve its chemical analysis capabilities for cooling water and materials to develop accelerator components, in addition to those required for environmental safety and protection.

Computing system: KEK will pursue research on the basic infrastructure for information technology, large computing systems, and supercomputers. In addition, KEK, as the host laboratory for the Belle II experiment, will develop and operate the computer and network technologies required for large-scale data analysis to be conducted at GRID centers around the world in a distributed manner.

Cryogenic and low-temperature technology: KEK will continue to supply accelerator systems and experiments that operate at low temperature or use superconductivity with a large amount of liquid helium. In parallel, KEK will develop advanced superconducting technologies for particle

accelerators, including next-generation high-field, radiation-resilient materials. KEK also hosts an in-house cavity fabrication plant for developing and proving techniques for the mass production of superconducting cavities. In addition, KEK, with its highly skilled engineering personnel, will lead an effort to advanced ultrahigh-precision machining techniques and apply them to the design and fabrication of equipment and experimental apparatuses.

2.4 Development of Detector-Related Technologies at KEK

As accelerator technologies bring “light” into the world of science, detector technologies will work as our “eyes” for examining the world. The technologies for particle detectors and instrumentation are indispensable for a variety of basic research, i.e., the very mission of KEK, including studies of elementary particles and nuclei as well as molecular imaging in material science or biology by means of SR, neutrons, and muons.

To advance detector technologies, KEK has established the Detector Technology Project to lead the following R&D by lateral efforts over the institutes in KEK.

- Superfine, ultrahigh-speed, and highly functional pixel detectors to detect X-rays in SR experiments or astronomy, measure decay vertices in particle physics, monitor beams in accelerometers, or search for dark matter
- High-sensitivity photon sensors for use at various experimental facilities for particle physics, nuclear physics, and muon experiments
- Time projection chambers (TPCs) with a liquid noble gas, which are highly suited for neutrino detection experiments, searching for possible proton decay or dark matter, and high-performance gamma ray detectors for use in medical or industrial applications
- Large-area imaging devices with micro-pattern gas detectors (MPGD), which are effective in next-generation neutron experiments as well as in particle and nuclear physics experiments
- Superconducting devices that enable ultrahigh-sensitivity detection of quanta associated with the cosmic microwave background (CMB), cosmic neutrino decay, and dark matter or terahertz imaging
- Supporting technologies such as mechatronics, micro-electronics, and low-temperature engineering

Many of the results of these activities have already received international acclaim. KEK will pursue these efforts with continually optimized priorities and content according to the future directions of experiments it supports.

Technologies originally developed for fundamental science are currently expected to be applied to next-generation electron microscopes, high-performance visualization devices using X-rays and neutrons, advanced therapy using a particle beam, or sophisticated medical diagnostics. Therefore, diversification of the R&D effort in anticipation of such spin-offs is becoming a common trend in major accelerator laboratories worldwide. KEK will incorporate these efforts as an increasingly important part of its mission and will act strategically while formulating an international collaborative framework.

2.5 KEK as a Center for International Cooperation, Human Resource Development, and Social

Contribution

As project sizes increase, project periods are extended, and the required technologies become more demanding, global collaborations are becoming ever more vital to the success of large-scale accelerator projects at all phases of their R&D, design, and construction. KEK intends to serve as a major international center for accelerator R&D with these facts in mind.

The growth of accelerator projects in terms of their size and applications indicates an acute need for aggressive human resource development in the field of accelerator science. KEK, an institution that operates cutting-edge accelerators, will actively host or participate in various domestic and international accelerator schools, in addition to offering courses at the Graduate University for Advanced Studies (SOKENDAI).

Although the main research objective of KEK is basic science, the technology and knowledge earned here should find many opportunities for application. KEK will actively serve as a conduit for society at large to effectively harvest the benefits of this type of work.

3. Strategy for the Next Five Years (2014–2018)

3.1 J-PARC

J-PARC is a multi-purpose accelerator complex at which a wide range of studies are pursued to understand the origin and structure of matter and living systems using high-intensity proton beams. The research infrastructure at J-PARC consists of the Neutrino Experimental Facility, the Hadron Experimental Facility, and the Materials and Life Science Experimental Facility (MLF), which are supported by expertise in basic technologies in particle accelerators, superconductivity, radiology, computer science, and other fields. During the period covered by this Roadmap, KEK will pursue scientific studies at J-PARC by taking advantage of its high-intensity proton beams so as to contribute decisively to future progress in relevant research fields as follows. In particle and nuclear physics, J-PARC, together with SuperKEKB, will be a driving force in Japan for research at the intensity frontier, complementing efforts at the high-energy frontier at the LHC or ILC. In material and life science, J-PARC will serve as a leading quantum beam infrastructure complex, together with the PF and Slow Positron Facility, by providing superb neutron beams and muon beams with unprecedented quality and quantity of intensity, resolution, and sample environment. For these purposes, the accelerator facilities at J-PARC will rapidly realize their design performance, as discussed later, while investigating paths for future upgrades.

J-PARC Neutrino Experimental Facility

KEK's neutrino research in the next five years will focus mainly on measurements of neutrino mixing with improved precision in the T2K experiment, and on R&D toward the next generation of the long-baseline neutrino oscillation experiment.

The T2K experiment has realized a major achievement in observing the transition of muon neutrino states into electron neutrino states (the appearance of electron neutrinos) for the first time worldwide. The next immediate goal of this experiment is to improve the precision of the measurement with increased intensity of the beam from the MR, with the aim of measuring the ν_e appearance probability within <10% by bombarding the target with $\sim 8 \times 10^{21}$ protons (POT). High-precision measurement of muon neutrino disappearance is expected to enable the determination of $\sin^2 2\theta_{23}$ within $\sim 1\%$ and Δm_{23} within $\sim 3\%$. When combined with the results of neutrino experiments at nuclear reactors and measurements of atmospheric neutrinos, it could

possibly set an important constraint on CP violation and on the mass hierarchy in the neutrino sector, offering a clue to solving the mystery of the matter dominance of the Universe.

The goal for the next generation of long-baseline neutrino oscillation experiments is to obtain decisive information on CP violation and mass hierarchy in the neutrino sector. This effort requires long-term availability of a highly stable MW-class proton beam and a gigantic detector with a sensitivity that far surpasses that of Super-Kamiokande. Such a detector, if realized, would also be indispensable in the search for nucleon decays and observation of cosmic-relic neutrinos. Candidate schemes for this detector system include a huge, megaton-class water Cherenkov detector (Hyper-Kamiokande) and a 100-kiloton-class liquid argon TPC; the technical development of the Hyper-Kamiokande scheme is currently at a more advanced stage. During the period covered by this Roadmap, KEK will collaborate with the Institute of Cosmic Ray Research at the University of Tokyo on refining the proposal for the next long-baseline experiment and will work toward realization of a MW-class proton beam at J-PARC. The latter effort will evolve into studies on further upgrades of the accelerator and neutrino beam line, R&D on which will be pursued in parallel. The R&D on a liquid argon tracking detector will also continue, as it is considered promising as a technology for high-performance neutrino detectors of the future.

J-PARC Hadron Experimental Facility

Research at the Hadron Experimental Facility at J-PARC has been thriving, with studies on the strong interaction such as the physics of nuclei with strangeness and hadrons, and on flavor physics, as exemplified by the search for rare decays of K mesons. The priority subject during this Roadmap period is to complete construction of the new primary proton beam line in collaboration with the Research Center for Nuclear Physics (RCNP) of Osaka University and others, and to make steady progress on experimental studies in nuclear and hadron physics, such as variations in meson mass shifts within nuclear matter and the search for muon–electron conversion.

For further pursuit of diverse and concurrent experimental programs in nuclear, hadron, and flavor physics, based on the outcome of the preceding experiments, plans will be developed for the introduction of new beam lines with novel features in the extended area, thereby expanding the capacity and capabilities of the Hadron Experimental Facility. This will be undertaken in collaboration with partner institutes including RIKEN and will aim to meet the demands of scientists in relevant fields and to serve as the world’s major center of excellence in nuclear, hadron, and particle physics.

Parallel studies will examine upgrading of the J-PARC accelerator in order to advance the experimental frontier using slow-extracted beams. The addition of a stretcher ring is a possibility that would allow an increase in the beam intensity with improved stability and longer extraction times for slow extraction of the high-intensity beam. The acceleration of heavy ions is yet another possibility, which may prove to be crucial in the future, depending on the progress in this field worldwide.

Materials and Life Science Experimental Facility (Neutron Science Facility)

The goal of the Neutron Science Facility at J-PARC’s MLF is to contribute decisively to major advances in the materials and life sciences by providing the world’s highest-intensity pulsed neutron beams. The present equipment at KEK is already being pushed to the limits of resolution, dynamic range, and sample environment under extreme conditions. Efforts will be made to achieve and exceed their design performance by introducing, for instance, an improved special sample environment. In addition, in collaboration with the JAEA, proactive measures will be taken to take

full advantage of the facilities at the MLF and facilitate research on a wide range of subjects, such as near-surface structure and dynamics, the dynamics of strongly correlated electron systems, the science of energy conversion materials, the hydrogen-induced properties of materials, and the fundamental properties of neutrons.

In keeping with the theme “Hydrogen and Spin in Matter” discussed in Section 1, efforts will be made to reach the ultimate sensitivity in spin measurement of neutrons, in addition to obtaining extreme performance in resolution, dynamic range, and sample environment. In parallel, new equipment will be built and fully commissioned, including polarization analysis neutron spectrometers that reveal the detailed magnetic structure and dynamics of materials with spin analysis of polarized neutrons, and neutron spin echo spectrometers that can precisely measure quasi-elastic scattering of neutrons and detect neutron spin precession.

Materials and Life Science Experimental Facility (Muon Science Facility)

The goal of the Muon Science Facility (MUSE) at J-PARC’s MLF is to fully commission the S-line with several branches, together with the U-line (ultra-slow muon beam line), which is currently under construction, and to facilitate high-quality μ SR experiments at beam lines dedicated to special devices. The goal is major advances in research relevant to the key phrase “Hydrogen and Spin in Matter” in the muon area during the next five years. In addition, a platform for performing characteristic X-ray analysis with negative muons will be provided for research in a wide range of applied fields ranging from archeology to life science. These undertakings will expand the user community as well as the research frontier and thus will expand the J-PARC MUSE, as part of the quantum beam platform complex of KEK IMSS, into a world-class stronghold of muon science.

In addition, the base facility of the H-Line, when completed, will support fundamental research in physics such as precision spectroscopy of muonium atoms produced by high-intensity beams and measurement of the anomalous magnetic moment and electric dipole moment of muons (g-2/EDM).

Accelerator Upgrades

The highest-priority task at J-PARC in the next five years is to increase the beam intensity of the 3 GeV Rapid Cycling Synchrotron (RCS) and the MR. A prerequisite for this task is an upgrade of the injector linac. Its beam energy will be increased from 181 MeV to 400 MeV and the peak current will be increased from 30 mA to 50 mA in JFY2013. Delivery of a 1 MW (design intensity) proton beam from the RCS to the MLF is to follow at the earliest possible time. The goal at the MR in the next five years is to provide a 750 kW beam for the T2K experiment with fast extraction and a 100 kW or higher-power beam for experiments at the Hadron Experimental Facility through slow extraction. These goals will be realized by adopting a higher repetition rate of the MR and deploying new magnet power supplies with improved stability. These efforts will be conducted in parallel with studies on the next upgrade paths for the accelerator to support future experiments at the neutrino facility and Hadron Experimental Facility. Key considerations there include a major increase in the beam power beyond the current design for neutrino experiments and a significant increase in the time availability of the beam in addition to its power for hadron experiments.

3.2 SuperKEKB/Belle II

The upgrade of KEKB into SuperKEKB will increase the peak luminosity by a factor of 40, allowing the detector facility to accumulate 50 times more data (50 ab^{-1}) than what was available for Belle. This is expected to provide opportunities for the discovery of phenomena, such as CP violation,

induced by physics beyond the standard model and of the signature of new higher-mass-scale physics as traced in the decays of B mesons, charmed mesons, and tau leptons. The properties of new hadronic states consisting of four or more quarks could also be elucidated.

The upgrade of the KEKB accelerator into SuperKEKB is a major undertaking that incorporates a “Nano-Beam Scheme” that squeezes the vertical beam spot size at the interaction point down to approximately 50 nm (KEKB had a beam size of $\sim 1 \mu\text{m}$ at the interaction point). It also involves an increase in the stored beam current by an ambitious factor of 2, which calls for the mobilization of many cutting-edge accelerator technologies. The detector facility will have all of its components inside the solenoid magnet replaced and the data acquisition system completely renovated with state-of-the-art systems.

The upgrade program of the accelerator and detector facility began in JFY2010 and is proceeding nearly on schedule, aiming at startup of accelerator commissioning in JFY2014 with physics data acquisition to begin in JFY2016. Improvements in accelerator performance with high current, low emittance, and ultra-small beta values at the beam collision point toward the design peak luminosity will be pursued in the following four to five years. The goal is to accumulate the target integrated luminosity in around 2020. Efforts to address numerous beam dynamics issues during this process and solutions developed through them are expected to facilitate the progress of accelerator science. The Belle II experiment is an international collaboration with more than 400 members from approximately 70 universities and laboratories in about 20 nations and regions. By supporting this collaboration and hosting its experiment, KEK will serve as a global center of excellence for scientists in the relevant fields from both Japanese universities and abroad.

The Belle II experiment allows the exploration of new physics in a wide range of channels because of its clean experimental environment, which is provided by electron–positron collision processes. Only the B factories at electron–positron collisions permit the measurement of processes such as $B \rightarrow l\nu$, $B \rightarrow D^{(*)}\tau\nu$, and $B \rightarrow K^{(*)}\nu\nu$. These processes are sensitive to the existence of charged Higgs bosons and other new physics, and will be the subject of intense study. They are expected to make important contributions to the understanding of new physics, which complements the search for new physics at the LHC and the B meson decay results from the LHCb collaboration. With the accumulation of an integrated luminosity of a few ab^{-1} at SuperKEKB, a series of important results are anticipated, and Belle II will serve as the vanguard for the discovery of new physics in combination with a theoretical understanding of hadron structure based on lattice QCD calculations.

3.3 LHC/ATLAS

Since the discovery of a new particle at around 126 GeV, the critical research objective at LHC has been to raise the beam collision energies closer to the design specifications, thereby determining the properties of this particle, a likely candidate for the long sought-after Higgs boson, and exploring phenomena that give pointers beyond the standard model. This will be done starting in 2015 following consolidation work to be conducted toward the end of 2014. KEK, as a member institute in the international collaboration ATLAS, together with Japanese universities, will be part of the driving force in this research.

Because the LHC offers a unique opportunity for energy frontier research in the next decade or longer, and the sensitivities for higher-energy phenomena are improved by accumulation of the integral luminosity in proton–proton collision experiments, continued luminosity improvement at the LHC throughout the 2020s is a critical mid-range strategic path to world-class high-energy physics. This logically necessitates a set of upgrades of both the accelerator and detector facilities

to be implemented in the first half of the 2020s, preparation toward which has to begin around 2015 in parallel with the experiments in the current configuration. KEK, with its successful track record of contributions to the LHC accelerator and the ATLAS detector, will be one of the leading members in the required upgrade programs and the associated international collaboration. Possible areas of contribution from KEK include the development and construction of superconducting magnets near the beam collision points, particle trackers capable of handling a high-intensity beam environment, and muon triggers. Their details are to be worked out in consultation with CERN.

3.4 ILC

Hadron colliders and lepton colliders have been serving as the pair of wheels that allowed high-energy physics to make monumental progress in the past several decades and reach its present state. The ILC is poised to unveil the nature of a new particle that was recently discovered as a candidate for the Higgs boson at the LHC and to deepen the understanding on other possible new observations to follow there. This is done at a center-of-mass energy region around 500 GeV by fully exploiting the features of a lepton collider, which offers an experimental environment ideal for decisive, high-precision measurements. The ILC is expected to lead to an elaborate understanding of the spontaneous breakdown of electroweak gauge symmetry, bringing particle physics into a new stage. The Japanese team has been playing numerous key roles in the R&D of the accelerator and detectors for the ILC and is naturally expected by its colleagues worldwide to step up its effort. As one of the leading partners in the Global Design Effort for the ILC, KEK has been steadily performing R&D on the superconducting RF and other accelerator-related technologies, driving the international effort that led to the completion of the ILC Technical Design Report in 2012. It has also been engaged in specific work toward realization of an accelerator facility that can produce suitable energy ranges in response to the discovery of the new particle at LHC. The aim is to begin operation of the ILC in the 2020s so as to obtain optimal physics results through synergy with research activities at the LHC. KEK will play a central role in creating an international preparatory group which leads the detailed engineering design effort and other related activities, which are needed toward groundbreaking of the linear collider project to be hosted in Japan within a framework of a global collaboration during the period covered by this Roadmap (2014-2018).

3.5 Photon Science (Synchrotron Radiation Research)

As a core site for SR use in Japan, KEK is committed to continue fulfilling the research demands of the SR user community. KEK will therefore build and operate a 3 GeV-class storage ring-type high-brilliance light source that is both advanced and versatile, supporting breakthrough developments in photon science. In this way KEK will play a leading role in the future advancement of worldwide SR research.

Until the 3 GeV-class storage ring-type high-brilliance light source is operational, KEK will continue to provide users with stable operation of the PF and PF-AR, as core facilities for SR use in Japan. KEK will strongly promote leading-edge joint research in collaboration with universities and other research institutions, and will continue to support a wide range of research fields that use SR as an essential tool in material and life sciences. The insertion device beam line in particular, provided in the plan for improvement of the straight sections of the PF ring, will give a powerful boost to research in many fields. These include researches on the physical properties of strongly correlated solid materials, surface and interfacial physical properties, surface chemical reactions, and soft materials and functional polymeric materials. Another area is structural biology research by means of protein structure analysis. In the PF-AR, a new direct injection beam line is being installed during the construction of SuperKEKB. Its use will reduce the emittance at full-energy injection and stabilize the beam intensity when a 6.5 GeV beam is injected in top-up operation. With the

combined effects of improved brilliance and higher average current, a five-fold increase in beam intensity is expected. As a result, it will be possible to conduct advanced material science research using high-pressure X-ray diffraction measurements of microcrystalline samples and time-resolved X-ray measurements of dilute samples, both of which have been difficult to perform up to now.

KEK earlier constructed and operated a compact energy recovery linac (c-ERL), for conducting R&D on the ERL as a future light source and to evaluate its feasibility. With recent progress in accelerator technology, however, it has become clear that most of the contributions to photon science expected from the ERL can be realized more quickly by building a 3 GeV-class storage ring-type high-brilliance light source. KEK has accordingly halted studies of the ERL as next-generation light source and has decided to aim for early realization of the storage ring-type high-brilliance light source.

The 3 GeV-class storage ring-type high-brilliance light source will achieve spatial resolution at the nanometer scale and meV-level energy resolution. It will make possible previously unachievable new research in several areas including studies aiming to clarify structural and electronic properties of heterogeneous substances, studies of chemical reaction dynamics that involve fluctuations, and elucidation of cellular regulation mechanisms. To promote these studies and other synchrotron radiation studies, closely coordinated joint research will be carried out, such as by forming a consortium mainly of universities and other SR research facilities. These joint research efforts, while actively encouraging personnel exchange, will seek to develop methodologies and human resources. In such ways, KEK will create leading-edge photon science, while continuing to support research in a wide range of disciplines that make use of SR.

Based on the above considerations, KEK will begin detailed design of the storage ring-type high-brilliance synchrotron light source in JFY2016, aiming for its early realization. The long-term plans beyond that will be studied anew.

3.6 New Development of Accelerator and Detector Technologies

In parallel with its large-scale projects, KEK is supporting other research programs that use the laboratory's unique in-house technical know-how regarding accelerators and accelerator-based experiments with its own ideas, such as measurement of the polarization of the CMB radiation and gravitational waves. KEK will contribute to such programs in collaboration with relevant communities and institutes according to their scientific merit and KEK's strengths.

KEK will contribute its expert knowledge and technical capabilities with respect to particle accelerators and detectors to their applications in industry and medicine. The development of boron neutron capture therapy (BNCT), induction synchrotrons (digital accelerators), and electron microscopes using superconductivity are examples of KEK's practical returns to society. In particular, medical applications open an area in which KEK will pursue opportunities to contribute by collaborating with relevant institutes on accelerators, detectors, and simulations that are effective for diagnosis and therapy.

KEK will also promote advanced accelerator technologies that have the potential to significantly improve the performance of future particle accelerators. They include the development of high-gradient particle acceleration with normal-conducting RF cavities, new acceleration schemes using laser-driven plasma, and the utilization of quantum beams of nanometer beam size and lasers. KEK will be committed to efforts toward their steady long-term progress.

4. Summary

KEK has been playing a central role in accelerator science in Japan by building and operating its 12 GeV PS, PF rings, TRISTAN, KEKB, and J-PARC. With studies of CP-violation in B-meson decays, KEKB made a major contribution to the progress of physics research by successfully confirming the validity of the Kobayashi–Maskawa theory.

It is reasonable to expect a continuous flow of scientific outcomes from the ongoing research programs at KEK in the next five years. The performance of J-PARC, a joint project of the JAEA and KEK, will meet its design goals, and the facility will advance research in particle physics, nuclear physics, and material and life science. The IMSS will transform itself into an international center of excellence as a research platform complex where a number of highly advanced quantum beams are used in a coordinated fashion. The operation of SuperKEKB, a radical upgrade from KEKB, will support the search for new laws in particle physics. In the photon science field, KEK will ensure continued stable operation of the PF and PF-AR to advance studies in photon science. In addition, KEK will draw up specific plans for a storage ring-type high-brilliance synchrotron light source as quickly as possible, and will work with related institutions toward its early realization. In these ways KEK will continue to play a leading role in the development of photon science in Japan as a whole.

The next five years will also be a critical period for preparing for longer-range research projects. The operation of a linear collider in the 2020s, concurrent with experiments at the LHC, is strongly desired by scientists at the energy frontier. The realization of a linear collider will require technical development and engineering design of the accelerator, as well as a detailed proposal for the project's organizational structure. KEK will play a central role in creating an international preparatory group to lead the detailed engineering design effort and other related activities, which are necessary for groundbreaking of the linear collider project. The project will be hosted in Japan within a framework of global collaboration during the period covered by this Roadmap (2014–2018). At J-PARC, a variety of research programs in particle physics, nuclear physics, and material and life science, including a large-scale neutrino experiment, call for increased beam power to be made available to users over an extended period of time. The specifics of the upgrade programs of the accelerator complex and user experimental facilities will be examined.

KEK will also take a strong initiative in applying its cutting-edge technologies to new accelerators and transferring these technologies to various applied fields such as medicine.

With coordinated and systematic efforts in collaboration with institutions within and outside of Japan, KEK will continue to play a leading role in accelerator science and related research fields into the future.

Members of the Research Steering Committee of the High Energy Accelerator Research Organization

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(May 24, 2013)

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(Partial revision: June 30, 2016)