Overview of J-PARC

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In the Japanese fiscal year JFY01, which started on April 1, 2001, a new accelerator project to provide high-intensity proton beams proceeded into its construction phase. This project, which is called the J-PARC (Japan Proton Accelerator Research Complex), is a joint project between two institutions, KEK and JAEA. We set a goal to achieve 1 MW proton beams at 3 GeV and 0.75 MW beams at 50 GeV. The construction period is 8 years, with anticipated first beams from the entire facility in the late fall of 2008, although the beams from the linac and 3 GeV were already accelerated and extracted in January and October 2007, respectively. In this chapter I describe the present status of the J-PARC.

1 What Is J-PARC?

J-PARC is the acronym of Japan Proton Accelerator Research Complex, which is under construction jointly by KEK (National High Energy Accelerator Research Organization) and JAEA (Japan Atomic Energy Agency). The facility is located in the Tokai campus of JAEA, which is about 60 km northeast of the Tsukuba campus of KEK.

This new proton accelerator is targeted at a wide range of fields, particle and nuclear physics, materials science, life science, and nuclear engineering. Figure 1 illustrates a one-page summary of sciences to be conducted at J-PARC. The atomic nucleus is made of protons and neutrons. When a low-energy proton (typically, at the energy of 1 GeV) hits the nucleus, the constituents of the nucleus, unstable nuclei, neutrons, and protons, will be ejected with the proton-induced spallation reaction. Among those, neutrons will be used at J-PARC for materials and life sciences. In addition, a copious production of pions is expected, so that the research on sciences with low-energy muons, for example, μSR or muonium science will be conducted. At higher beam energies, typically 50 GeV, the proton–nucleus collisions will produce kaons, high-energy neutrinos, anti-protons, etc. The usage of kaons

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and neutrinos is planned at J-PARC. The entire view of the J-PARC facility is illustrated in Fig. 2.

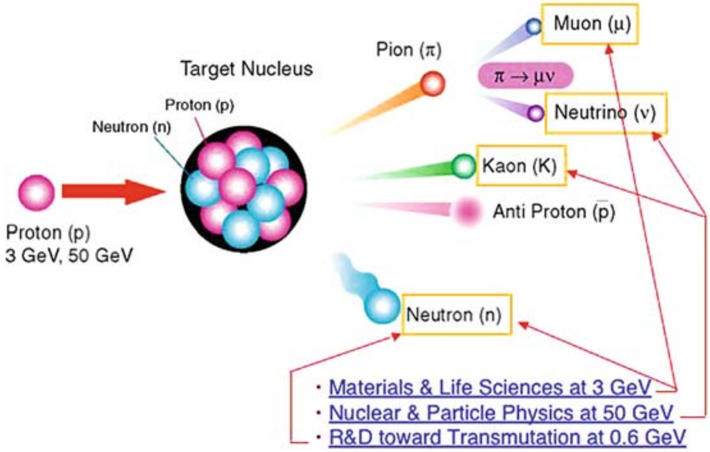

Fig. 1. Production of primary, secondary, and tertiary beams at J-PARC to be used for a variety of scientific programs.

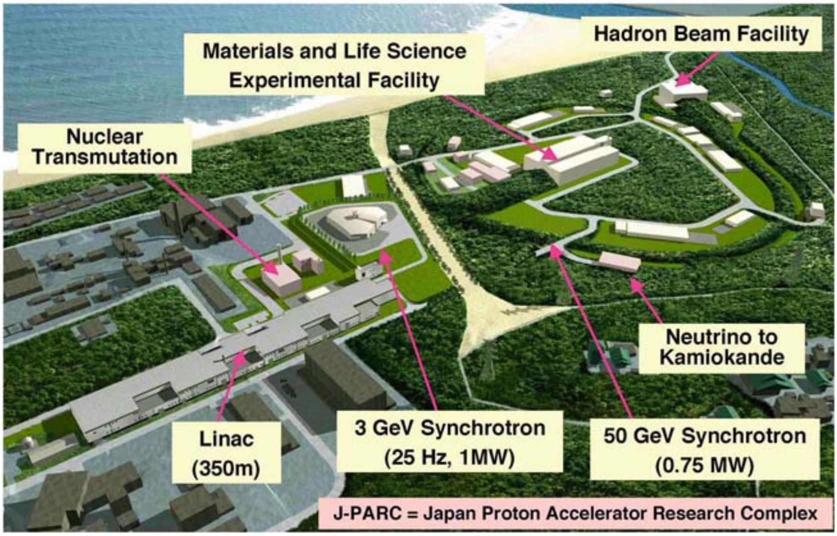

Fig. 2. The J-PARC facility.

J-PARC accelerator comprises the following components:

- 400 MeV (181 MeV on day-1) proton linac as an injector.

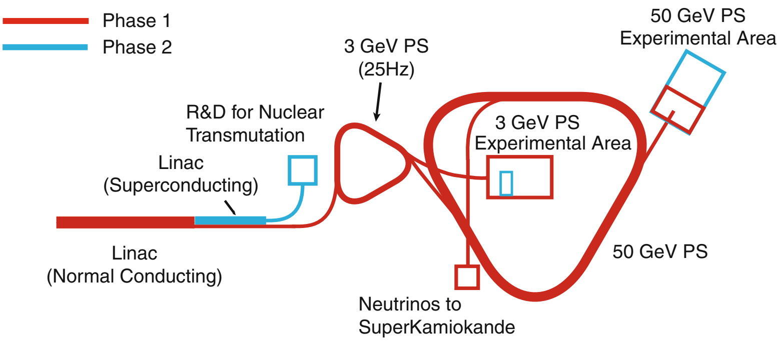

Fig. 3. Schematic diagram of the J-PARC facility. The project is divided into Phase 1 and Phase 2.

- 25 Hz 3 GeV proton synchrotron with 1 MW power, called the 3 GeV RCS (RCS = rapid cycle synchrotron).
- 50 GeV MR (MR = main ring) proton synchrotron with slow and fast extraction capabilities for nuclear–particle physics experiments.

The schematic diagram of the facility is shown in Fig. 3. The project is approved in two phases. In the first phase of the project, Phase 1, the linac up to 181 MeV, the 3 GeV RCS, and the 50 GeV MR (with an energy up to 40 GeV), together with three experimental halls, (a) an experimental hall for materials and life science, (b) a hadron experimental facility, and (c) a neutrino beamline, are included. Immediately after the completion of Phase 1, the linac energy will be recovered to the original design value of 400 MeV. In the second phase, Phase 2, the construction of a facility for R&D of nuclear transmutation, an expansion of the Hadron Experimental Hall, and an addition of beamlines and experimental devices in the Materials and Life Experimental Hall, etc., are planned. The upgrade plan is described later.

2 Accelerator and Facility Construction

The construction of the J-PARC facility started in 2001 and the provision of beams is set to commence in the late 2008. In January 2007 we succeeded in acceleration of proton beams through the linac. At the end of October 2007 the beam acceleration and extraction from the 3 GeV RCS was successfully achieved. The beam injection to the 50 GeV MR is planned in the spring of 2008. The schedule together with the entire view of the J-PARC facility is illustrated in Fig. 4. The present construction schedule, which was created in February 2006, has not been changed since then.

Concerning the facility construction, the groundbreaking ceremony was held in June 2002. Subsequently, construction work has started at a rapid

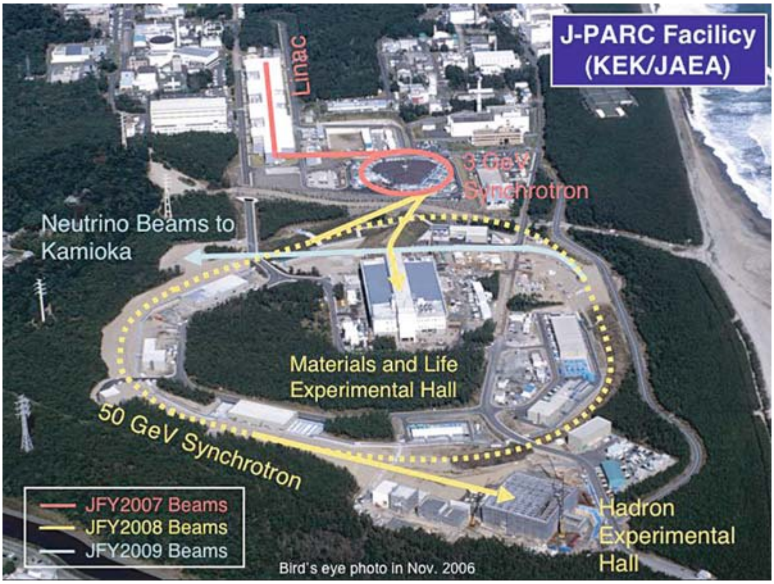

Fig. 4. An entire view of the J-PARC and the present construction plan.

speed. By now (February 2008), almost all the facility buildings, except for those for neutrinos, were completed.

2.1 Accelerator Components

At J-PARC an H^- ion source is connected to RFQ and then to a series of DTLs (drift tube linacs). At the end of October 2003, the first test for the DTLs (the first 20 MeV portion) was done at KEK. On the first day, 6 mA was successfully accelerated and in a week later, the acceleration of 30 mA was achieved.

The DTL is then connected to a series of SDTLs (separated drift tuber linacs) in order to accelerate to 181 MeV. As described earlier, the 181 MeV beam through the linac was obtained in January 2007.

In regard to the linac, a unique idea of the π-mode stabilizing loop, which is one of the devices invented at KEK to stabilize the fields in an RFQ, was adopted, which allows acceleration energy above 3 MeV with frequency range from 300 to 400 MHz. Also, a new drift tube linac (DTL) has newly developed coils for the electro-quadrupole magnets in order to improve a packing factor. The entire scenery of the linac is shown in Fig. 5.

The linac beam will, then, be injected to the 3-GeV RCS (Fig. 6) and to the 50-GeV MR (Fig. 7). About 96% of the beams at the 3 GeV will be extracted to the Materials and Life Experimental Hall and the remaining 4% of the beam will be sent to the 50-GeV ring. The J-PARC synchrotron

Fig. 5. Linac for J-PARC. The beam is already available.

Fig. 6. 3-GeV synchrotron for J-PARC (*left*) and a new RF sector (*right*).

has many unique features. For example, an arrangement of synchrotron magnets was designed so as to have no transition energies in the ring. A novel idea of the RF cavity to attain a high-voltage gradient was implemented by using a specific and new magnetic alloy, called the Finemet. At the 3 GeV, 20 different types of ceramic vacuum pipes are prepared in order to avoid "eddy currents" induced by a rapid cycle operation of the synchrotron magnet (25 Hz).

Due to the budget constraint, the initial beam energy for the 50 GeV PS will be 40 GeV. Later, when an additional budget to allow the storage of an electricity power is funded, a full 50-GeV operation is possible. In addition, due to budget constraint, the initial beam energy of the linac is 181 MeV. The recovery of the beam energy to 400 MeV will be made as soon after the completion of Phase 1.

Fig. 7. 50-GeV synchrotron for J-PARC.

2.2 Experimental Halls

At J-PARC three major experimental halls will be prepared. The first one is an experimental hall to use 3-GeV beams, called the Materials and Life Experimental Hall. One of the most useful aspects in the research at J-PARC is a broad application by using neutron and muon beams. The 3-GeV RCS provides 25 Hz proton beams. This means that the pulsed neutron/muon beams can be obtained 25 pulses per second. The proton beam hits the first production target to produce muons. There, 5% of the full beam power will be used. See Fig. 8 (left) for the muon production target. The remaining 95% power will be sent to the final target where neutron beams will be produced. An expected total beam power is 1 MW. The present world frontier is at the level of 0.1 MW, so that the most powerful neutron beams are available at J-PARC. For pulsed neutron beams, 23 beamlines will be prepared, as shown in Fig. 8 (right). About 10 beamlines will be available at the time when the first beams are available.

On the other hand, the 50 GeV MR has two beam extraction lines. The slow extracted beam will be delivered to the Hadron Experimental Hall, where kaon beams will be prepared for variety of experiments, in addition to primary proton beams. This area is called the Kaon Factory. Three major beamlines, (a) charged kaon beams with 1.8 GeV/c, (b) neutral kaon beams, and (c) kaon beams with 1.1 GeV/c, are under construction. Requests from users to use this hall are rapidly increasing, since many experimental proposals including the usage of primary beams, muon beams, etc., have been sent to the J-PARC. In order to accommodate all these requests, the Phase 1 experimental hall is already too small. An expansion of the hall is planned as one of Phase 2 projects. Figure 9 shows the present view of this Hadron Experimental Hall.

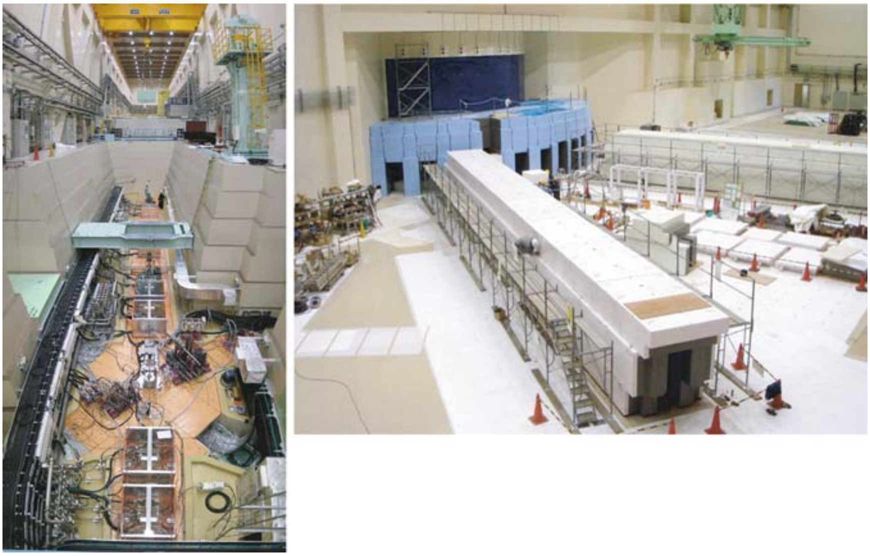

Fig. 8. *Left*: Muon source. The beam comes from the back toward the front direction. Four beamlines for pulsed muons will be prepared. *Right*: Pulsed neutron experimental hall. Both pictures were taken in August 2007.

Another beamline from the 50 GeV MR is a fast extraction line which will be used for the production of neutrino beams. Here, muon neutrino beams, ν_μ, will be created and they are sent to the Super-Kamiokande neutrino detector which is located at 295 km west of J-PARC.

This beamline is illustrated in Fig. 10. Extracted proton beams are bent sharply by a series of superconducting magnets toward the west direction.

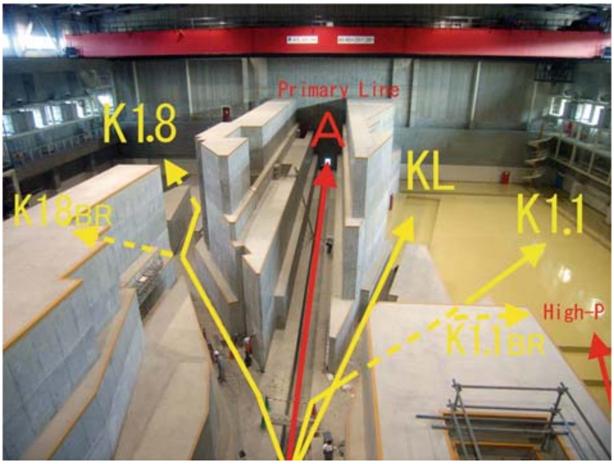

Fig. 9. Hadron Experimental Hall as of August 2007.

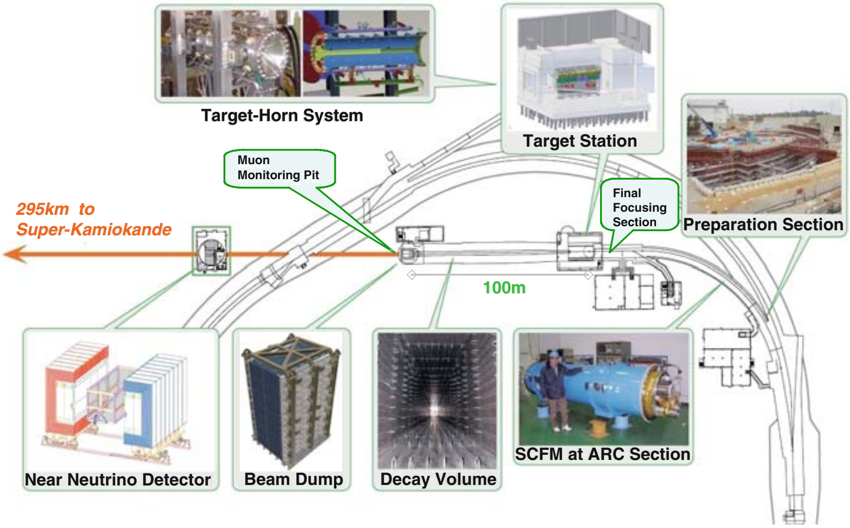

Fig. 10. Neutrino beamline at the J-PARC. The neutrino beam will be sent toward the west direction where the Super-Kamiokande detector exists.

Then, at the target area the beam is sharply focused by the device called the "horn." A copious pions are produced there. Then, the pion decays into a muon and muon neutrino ($\pi \rightarrow \mu + \nu_\mu$) when the pion traverses through the area called the "decay volume." The muon neutrino will be detected immediately after the tunnel of the neutrino beamline by the detector called the "Near Neutrino Detector." After that, the neutrinos will be measured by the second detector which is placed at 295 km west of the J-PARC location. This second detector is the Super-Kamiokande.

3 Examples of Sciences at J-PARC

The J-PARC is a multi-purpose facility in which scientific research in nuclear and particle physics, materials science, life science, nuclear engineering, etc., will be conducted. In addition, the usage by industries is highly encouraged at J-PARC. In this chapter, I show very limited examples only.

3.1 Neutrino Experiment, T2K

The first experiment is related to the neutrino mass and mixing. It is known that, from the most fundamental principle, there are no reasons to assume that the neutrino mass is zero, although it has been believed for many years that the neutrino carries zero mass. In a recent experiment at Super-Kamiokande [1, 2], where atmospheric neutrinos were detected, it was demonstrated that muon neutrinos ν_μ from the sky were converted to tau neutrinos ν_τ while traversing through the Earth. This phenomenon proved evidence on the existence of neutrino oscillation. Because this oscillation can occur only when the neutrino carries a finite mass, this measurement demonstrated the existence of a finite mass of neutrino.

A recent K2K experiment [3] using ν_μ beams from the KEK 12-GeV accelerator to detect ν_μ at Super-Kamiokande showed an additional evidence that ν_μ would oscillate while traversing from KEK to Super-Kamiokande. Furthermore, a later SNO result [4] and, independently, a KamLAND experiment [5, 6] show that neutrinos from the Sun (primarily ν_e) also oscillate due to a finite mass of neutrinos.

At the forthcoming J-PARC an anticipated ν_μ neutrino flux is by 100 times stronger than the flux obtained at the 12-GeV PS at KEK. Therefore, precise measurements of the neutrino mass can be expected at the 50-GeV facility of J-PARC. Experimental group also expects to observe $\nu_\mu \rightarrow \nu_\mathrm{e}$ oscillation by observing ν_e appearance at Super-Kamiokande (see Fig. 11). By observing this new mode, a new mixing angle, θ_{13}, can be determined. This T2K experiment, thus, will determine a completely new and unknown mixing parameter, as illustrated in Fig. 12.

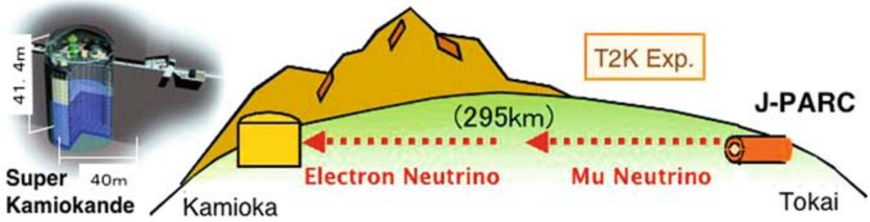

Fig. 11. T2K (Tokai to Kaimioka) experiment using ν_μ beams from J-PARC.

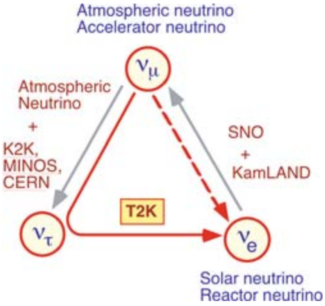

Fig. 12. Three neutrinos and the goal of the T2K experiment. The mixing between the first and the third neutrinos will be measured.

3.2 Hadron Experiments with Kaon Beams

At the Hadron Experimental Hall, many different pieces of experiments are planned. Details will be described by other author(s) in this book. Here, one or two examples are given.

One experiment is related to the mass of matter. It is known that over 99% mass of the visible matter of the universe is carried by atomic nuclei and, thus, by protons and neutrons. Each proton or neutron is made of three quarks. One puzzle, which has not been solved quantitatively until now, is an exact reason that the mass of proton (or neutron) is as heavy as $1\,\mathrm{GeV}/c^2$, whereas the quark mass is much lighter, being less than 1/100 of the proton mass. It is believed that the creation of a large proton mass is connected with spontaneous chiral symmetry breaking. The quantitative nature of this symmetry breaking needs to be further explored.

Theoretically, it is expected that this symmetry breaking can be studied by implanting a meson (which is made of quark and anti-quark) in the interior of matter under extreme conditions and, then, by measuring the change of properties such as the chiral order parameter [7, 8] in these conditions. Implanting mesons or baryons in the interior of nuclear matter and studying their properties in nuclear matter are, thus, extremely interesting.

Figure 13 illustrates the current status of properties of hadrons in nuclei. In a recent experiment [9] a hint of the existence of a meta-stable bound state of negative kaon (K^-) in the nucleus was discovered. If a kaon is implanted inside the nucleus, it was hypothetically predicted that this kaon might play a role as a catalyzer to induce the formation of an extremely high-density

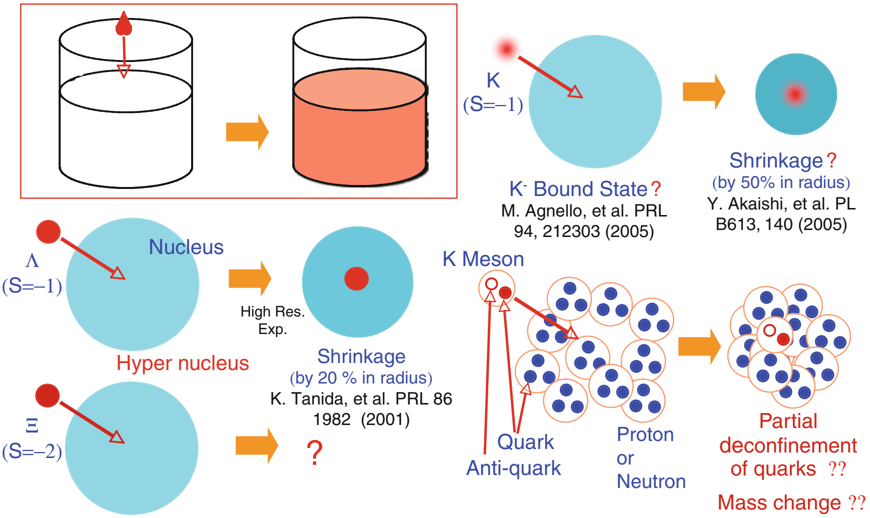

Fig. 13. Implantation of strange baryon or meson inside the nucleus, to be studied with kaon beams at J-PARC.

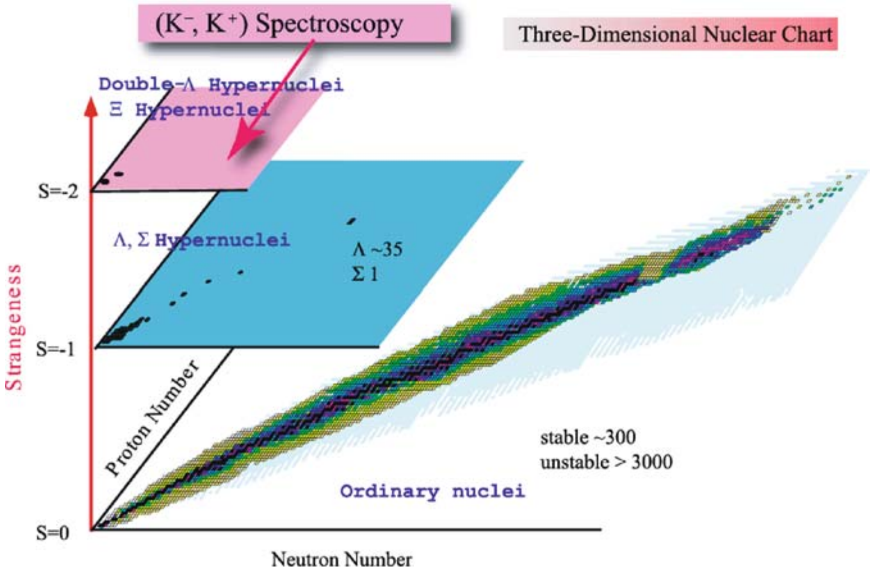

Fig. 14. Hypernuclear chart. Three-dimensional nuclear chart can be drawn when a strangeness freedom is incorporated.

system [10]. If the matter were compressed, the property of K^- could also change, as illustrated schematically in the lower right in Fig. 13. The change of meson properties inside nuclear matter would lead to important conclusions concerning the experimental study of chiral symmetry breaking, as hinted in Refs. [7, 8, 11].

Another example of hadron implantation inside the nucleus is a strange baryon implantation, called the hypernucleus. As shown in Fig. 14, three-dimensional nuclear chart can be drawn when the baryon freedom includes strangeness. The spectroscopy itself is interesting. In addition, in an earlier experiment [12] it was demonstrated that an implantation of Λ hyperon inside the nucleus induces a shrinkage of the nucleus. Detailed studies on strange baryons and strange mesons in nuclei are planned as day-1 experiments at J-PARC by using high-flux kaon beams.

3.3 Materials and Life Sciences

The J-PARC covers broad sciences other than nuclear and particle physics. The largest area is materials and life sciences. There, experimental studies will be carried by using pulsed neutrons and muons.

The neutron beam carries many unique features, as illustrated in Fig. 15. First, the neutron penetrates through the matter. This feature is unique, as compared to X-rays, since X-rays are easily reflected by a metallic substance, whereas neutrons go through any metallic materials. For example, the movement of automobile engine has already been studied with neutron beams. In

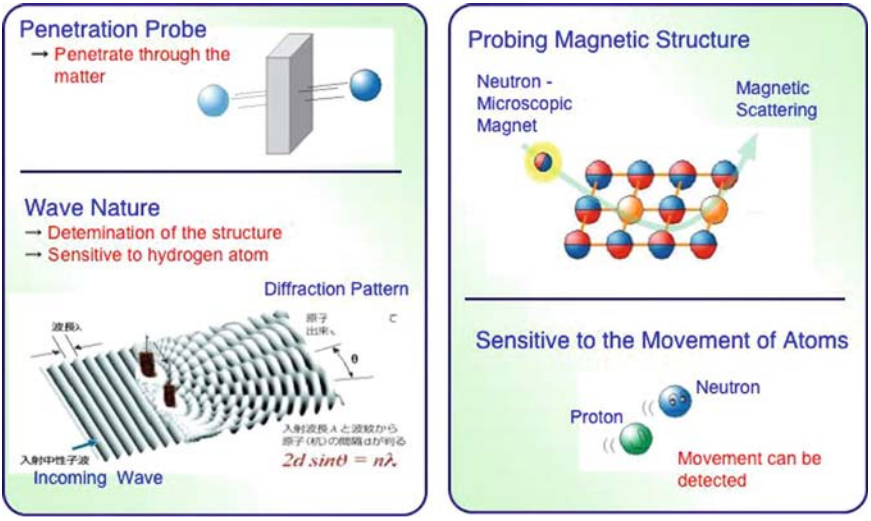

Fig. 15. Four unique features of the neutron beam.

the second, the neutron is a wave, so that it produces a diffraction pattern through a crystal. In particular, since neutrons interact with atomic nuclei instead of electrons, the neutron is very sensitive to atoms with small atomic number Z. In order to measure hydrogen, water, etc., with small Z, therefore the neutron beam is extremely powerful. In the third, the neutron carries a

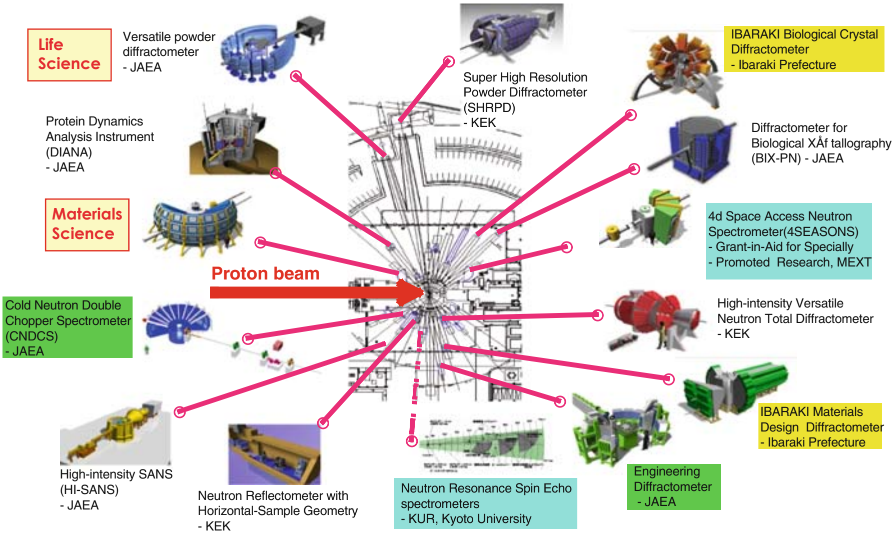

Fig. 16. Experimental devices being prepared for neutron beams.

magnetic moment. The magnetic structure of a crystal or any material can be studied with neutron beams. Finally, high-intensity neutron beams are very powerful for the study of the movement of atoms. This unique feature allows us to study a "function" of a protein in addition to the "structure" of the protein. Many experimental devices, as illustrated in Fig. 16, are being prepared for the study of materials and life sciences with neutrons.

4 Future of the J-PARC

4.1 J-PARC in the World

New facilities that are competing with, and/or comparable to, the J-PARC are being constructed in the world, as illustrated in Fig. 17. In the area of pulsed neutron beams a new facility called the SNS in the USA has been constructed, and the neutron beams have started to be used by experimental groups. This SNS will provide beams at the MW level, and this power is comparable to the power expected at the J-PARC. The ISIS at the Rutherford Laboratory in the UK is already sending pulsed neutron beams at 0.1–0.2 MW. The J-PARC together with the SNS and ISIS will form three regional centers for neutron sciences.

In the area of neutrino physics, the J-PARC, FNAL, and CERN will compete with each other in the area of accelerator-driven neutrino beams. The J-PARC has the advantage that it already has a working detector, the Super-Kamiokande. On the other hand, FNAL and CERN have the advantage that

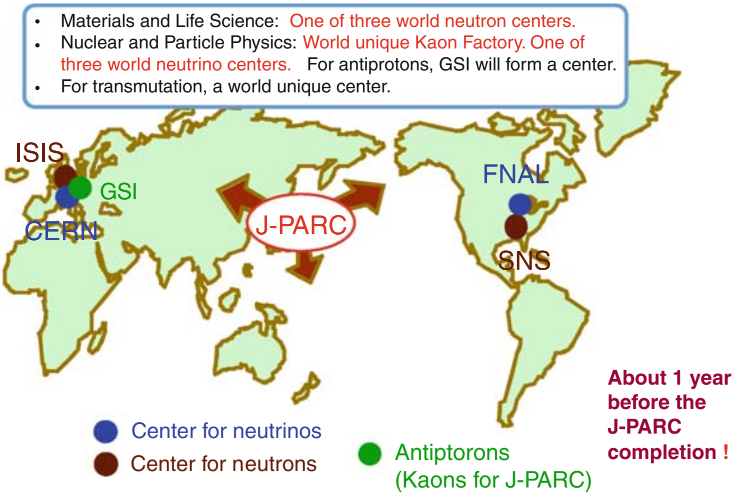

Fig. 17. J-PARC when compared with other competing and comparable accelerators in the world.

they already have neutrino beams. A strong competition exists among these three facilities in the future neutrino sciences.

Concerning the hadron physics, the J-PARC is unique in terms of kaon beams. This is the reason why J-PARC is called a unique Kaon Factory in the field of hadron physics in the world. On the other hand, a future facility called FAIR in Germany will produce intense anti-proton beams. Although there is a capability at J-PARC to produce anti-proton beams, the present arrangement is such that the anti-proton physics will be conducted at FAIR, whereas the kaon physics will be done at J-PARC. Other programs, such as programs using intense muon beams for flavor violation experiment and/or g-2 experiment, are being studied at J-PARC. In this area, a good coordination with FNAL fixed target program might have to be made.

4.2 Upgrades of the J-PARC

The present construction of the J-PARC will be completed in the spring of 2009. Many possible options after 2009 for upgrades are discussed. Described below is a list of major items that are currently under discussion:

- Neutrons and muons: How to fill the 23 beamlines for neutrons? So far, about 10 were funded. Concerning muons, one among four beamlines will be in operation in 2008. Others have to be filled after 2008.
- Hadrons: Unfinished beamlines, including neutral kaons, 1.1 GeV/c beamlines, and a primary beamline have to be completed. Also, in order to accommodate many users an expansion of the present hadron hall has to be done.
- Neutrinos: The power upgrade of the 50-GeV MR to above 1 MW must be done. Also, the detector at a distance of 2 km from the J-PARC is under discussion.
- Nuclear transmutation: This is the major item for Phase 2 in J-PARC, as illustrated in Fig. 3.
- Others: An energy upgrade of the main ring to 50 GeV must be done. Also, an issue on the table is the third extraction line from the 50-GeV MR. Other proposals, such as polarized proton beams at the MR, have to be considered as well.

All the above items are now under discussion at the Users Steering Committee at the J-PARC, where this committee is composed of representatives of user communities for the J-PARC. Among the items listed above, the program of nuclear transmutation is discussed at the Atomic Energy Committee of Japan, since this program is related to the policy of the waste disposal of long-lived radioactive materials produced in nuclear fuel plants. It is believed that the proton power required for the practical treatment of nuclear waste transmutation is on the order of 20–50 MW. Our J-PARC has a much smaller power when compared to these numbers. Thus, we plan to perform R&D studies to establish a concept of the accelerator-driven nuclear transmutation

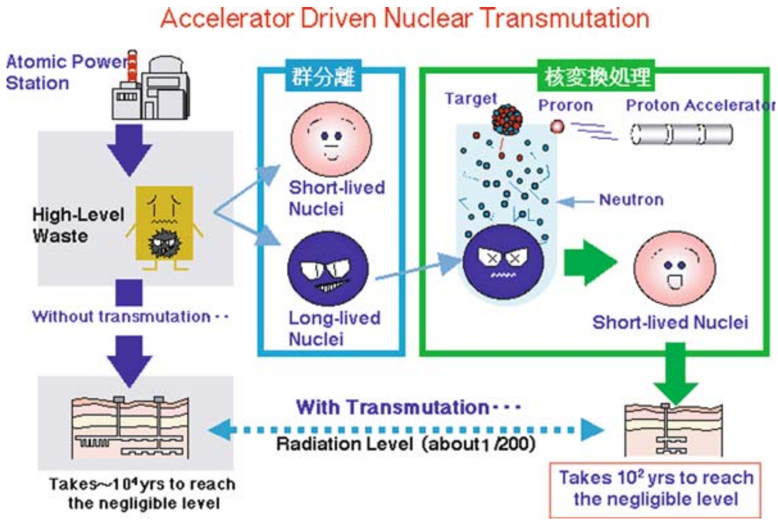

Fig. 18. Need of the nuclear transmutation program at J-PARC. The site for this program is reserved for the J-PARC, as illustrated in Fig. 2.

(ADT). The concept of the transmutation is illustrated in Fig. 18. Development of mechanical and nuclear engineering together with collection of nuclear reaction data under critical conditions will be the goal in our project.

4.3 Operation of the J-PARC

From the end of 2008 the J-PARC will start its operation. The J-PARC Center was created in 2006 to take a responsibility of the operation of J-PARC. This center is located under two institutions, KEK and JAEA.

Many infrastructures are being prepared: lodging, road access, users' office, visas, technical support, proposal handling, safety, etc. In addition, the project team is now working hard for the completion of the accelerators and the experimental halls and facilities.

Acknowledgments

At this opportunity, I would like to thank all the J-PARC members for their patient and energetic work on the completion of J-PARC. Also, I would like to thank all the administrative members of KEK and JAEA for their strong support of J-PARC.

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