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*Cover illustration:* Pictures of the entire view of J-PARC and the inauguration ceremony held on July 6 of 2009.
Establishment of the Asian Nuclear Physics Association (ANPhA)

On July 18, 2009 the Asian Nuclear Physics Association was officially launched in Beijing by representatives from China, Korea, Japan, and Vietnam.

The main objectives of ANPhA are:

1. To strengthen “Collaboration” among the Asian communities in nuclear research through the promotion of basic nuclear physics and its applications,

2. To promote “Education” in the Asian nuclear science communities through mutual exchange and coordination of resources,

3. To encourage “Coordination” among the Asian nuclear scientists for active utilization of existing research facilities, and

4. To discuss future planning of the nuclear science facilities and instrumentation among member countries.

Initially, the need of an organization like ANPhA was raised from time to time at the meetings of the Commission on Nuclear Physics (C12) of the International Union of Pure and Applied Physics (IUPAP) as well as at its Working Group (WG.9) on the International Cooperation in Nuclear Physics (ICNP). The first step was taken during the meetings of WG.9 and C12 in May 2008 held at CERN, where Shoji Nagamiya (KEK/J-PARC, Japan), Dong-Pil Min (SNU, Korea), Hideyuki Sakai (U. Tokyo, Japan), and Wenqing Shen (NSFC, China) met together after the dinner of WG.9 and agreed to launch an initiative to form an organization in Asia similar to NuPECC in Europe. In Asia, world-class facilities, such as RIBF at RIKEN and J-PARC at Tokai in Japan, a new initiative on a heavy ion accelerator in Korea, Heavy Ion Research Facility in Lanzhou (HIRFL), and BRIF (II) at CIAE in China, and so on, are in operation or being planned.

It was widely recognized among the member countries that systematically organized usage of these facilities was still missing and a collaborative scheme was highly desirable to make the best use of them. Thus, one of the major roles of ANPhA was to provide a common ground to discuss those issues in harmony. Another important role of ANPhA was to promote education in nuclear science among the Asian countries through various means.

The first preparation meeting was held in Tokyo, Japan on October 4, 2008 followed by the second one in Seoul, Korea on February 21, 2009.

On July 18, 2009 the Inauguration Ceremony took place in the Ying Jie Conference Center of Peking University in Beijing. First, the board members from China, Japan, Korea, and Vietnam were officially confirmed. These board members gave their official approval to the Bylaws. These initial board members were Weiping Liu, Yugang Ma, Guoqing Xiao, and Yanlin Ye from China, Tohru Motobayashi, Shoji Nagamiya, Seung-Woo Hong, Hideyuki Sakai, Jiaer Chen, Wenqing Shen, Shoji Nagamiya, Tohru Motobayashi, Weiping Liu, Yuxin Liu, Wooyoung Kim, Yanlin Ye, Wenlong Zhan, Takaharu Otsuka, Boqiang Ma, Hushan Xu, Yugang Ma, and Furong Xu.
Nagamiya, Takaharu Otsuka, and Hideyuki Sakai from Japan, Seung-Woo Hong, Wooyoung Kim, and Dong-Pil Min, from Korea, and Dao Tien Khoa from Vietnam. Second, for the first term Hideyuki Sakai was elected as the Chair of ANPhA, Dong-Pil Min and Yanlin Ye were elected as Vice-Chairs, and Tohru Motobayashi was later appointed by the Chair as Scientific Secretary.

During the Inauguration Ceremony, congratulatory addresses were given by Wenqing Shen (Deputy Director of NSFC), Wenlong Zhan (Deputy Director of CAS), Huanqiao Zhang (Chair of NPSC), Jiaer Chen (Former President of PKU), and Guangda Zhao (Director of the Scientific Committee of the School of Physics of PKU), which were followed by speeches by the ANPhA board members representing the nuclear physics communities in their own countries. The ceremony was also witnessed by professors Boqiang Ma, Yuxin Liu, and Furong Xu of Peking University. Finally, the commemorative photograph was taken (see Figure 1).

After the ceremony, the first business meeting of ANPhA took place. The main topics of the discussion were:
1. Invitation of new member countries and regions,
2. Preparation of documents for the existing research facilities and computing resources in member countries and regions,
3. ANPhA support for symposiums and schools,
4. Discussion on the long-range plan of ANPhA,
5. Decision on the second ANPhA meeting.

It is decided that the official ANPhA Office is located at the RIKEN Nishina Center in Japan. A very preliminary ANPhA home page is currently available at http://ribf.riken.jp/ANPhA/.

Concluding the first ANPhA board meeting, it was proposed to organize the First ANPhA Symposium on Asian Nuclear Physics Facilities on January 18–19, 2010 at Tokai, Japan. A visit to J-PARC for symposium participants will be also planned.

The next ANPhA board meeting will be held on January 17 (Sunday), 2010 in conjunction with the First ANPhA Symposium.

HIDEYUKI SAKAI
University of Tokyo
and
ANPhA Chair
Exciting Times for Japanese Nuclear Physics

J-PARC Overview
Eight years ago, the High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA) started work on a joint venture to construct a new proton accelerator at the highest beam power in the world. The new accelerator is targeted at a wide range of fields, using K-meson beams and neutrino beams to cover nuclear and particle physics and neutron beams and muon beams to cover materials science, biology, and nuclear engineering, where these beams will be created by bombarding high-power proton beams on nuclei at rest. The accelerator is called the J-PARC, which is an abbreviation for Japan Proton Accelerator Research Complex.

The plan was to complete the project in the spring of 2009. Actually, the construction went smoothly on schedule. We had the following beams from the accelerators: Neutron beams in May 2008, followed by muon beams in September 2008, K-meson beams in February 2009, and, finally, neutrino beams in April 2009. This year, therefore, is the first year for J-PARC to open its facilities to general users.

J-PARC will be open to the whole world as an international facility. We already have over 400 registered users in this facility from outside Japan. We expect that this number will increase as time proceeds. This project is also expected to boost levels of participation from the Asia and Oceanic regions in particular in the area of neutron-related fields. Work on the preparations to accommodate non-Japanese users is also going ahead in cooperation with local governments including Tokai-Mura Village and the Ibaraki Prefecture.

Three Experimental Facilities
The J-PARC consists of three accelerators (Linac, 3 GeV synchrotron, and 50 GeV synchrotron) together with three experimental facilities. The latter three are (1) neutrino experimental facility, (2) hadron experimental facility, and (3) materials and life experimental facility, as shown in Figure 1.

Among three facilities, two are mainly focusing on nuclear and particle physics. In the neutrino facility, the entire purpose is to measure

Figure 1. Entire view of J-PARC.

Figure 2. Neutrino oscillation experiment called T2K.

Figure 3a. Hypernuclear studies to fill up three-story nuclear chart.
neutrino oscillation. In this experiment, called T2K, a particular interest is to measure electron neutrino at Super Kamiokande to measure a mixing angle between the first and third neutrinos, $\theta_{13}$, as illustrated in Figure 2.

On the other hand, the hadron facility carries many different experimental programs. One big one is to measure hypernuclear spectroscopy by aiming at filling a three-story nuclear chart, as described in Figure 3a, in order to study strangeness effect in a nuclear chart. The second experiment is to study the question of the origin of proton and neutron mass by measuring meson implantation inside the nucleus, as schematically illustrated in Figure 3b.

The third experiment is to study rare decays of $K_L$ to $\pi^0\nu\bar{\nu}$ to study CP violation. Many experiments other than these three are being planned in the hadron hall. Details will be described later in this issue.

The research goals of the third and largest experimental facility are materials and life sciences, by using pulsed neutron and pulsed muon beams. Since these sciences are beyond the subject of this journal, I shall skip describing them.

**From 2001 to 2009**

This project started in the spring of 2001. Immediately after the approval of this J-PARC project, a project team was officially created by the agreement of two institutions. The ceremony for this event is shown in Figure 4 (upper). On the right-hand side of the photo are representatives of KEK and on the left-hand side are representatives of JAEA.

After this event a Japanese-style ground-breaking ceremony was held, as shown in Figure 4 (lower). It took exactly eight years for this project to be completed. Meanwhile, the team was changed from the project team to the J-PARC Center in 2006. It was anticipated that the J-PARC Center would connect smoothly from the construction phase to the operational phase, as shown in Figure 5.

The project was completed in the spring of 2009, as described before. The construction schedule was frozen in early 2006 immediately after the start of the J-PARC Center. Since then, the schedule was kept almost on time (within a month) for the entire project.

The inauguration ceremony to celebrate the completion of the construction was held on July 6, 2009. This ceremony also celebrated the usage of four facilities—neutrons, muons, kaons, and neutrinos—by the public users. Photos from this inauguration ceremony are shown in Figures 6 and 7.

**Internationalization of J-PARC**

A unique feature of the J-PARC can be found in its usage by international users. As shown in Figure 8, the project is unique in many aspects. For pulsed neutrons the J-PARC will form one of the three largest centers in the world, with SNS in the United States and ISIS in the United Kingdom. Other new facilities follow these three, such as Chinese spallation neutron source, European spallation neutron source (ESS) in Sweden, and so on. In the field of neutrino science, the J-PARC...
also forms one of three world centers, with FNAL in the United States and CERN in Switzerland. Concerning hadron physics, a new facility in Germany, called FAIR, will complement us by having anti-proton beams in FAIR while kaon beams are in J-PARC.

Therefore, one of the most urgent issues for the J-PARC is to prepare or to allow an easy access for world users. We are making significant efforts on this. For example, we created a “Users Office” to provide foreign (and domestic) users with many services. Also, we are preparing lodgings as quickly as possible. Recently the decision was made at KEK to construct 50 additional rooms during the next year.

Also, ANPhA (Asian Nuclear Physics Association) was created under IUPAP. The first chair of this Association is Professor H. Sakai in Tokyo. A detailed article is written in the following Editorial Note. We would like to utilize this Association to promote nuclear physics collaborations in Asia–Oceanic countries.

Unfortunately, the access by international users has not been well prepared at J-PARC (also not very well at all institutions in Japan). I, however, would like to improve this situation significantly in the future.

J-PARC has started its operation. Although we have to improve accelerator performance significantly in the future, the facility is now open to all the users of the world. We shall make every effort to allow as many international users as possible. Please plan to use J-PARC as much as you can.

Figure 6. Representatives of three parties (KEK, J-PARC Center, and JAEA) shook hands together on the occasion of the inauguration ceremony on July 5, 2009.

Figure 7. International guests from around the world on the occasion of the inauguration ceremony of J-PARC on July 6, 2009.
Figure 8. J-PARC as one of the world centers.

editorial

Erratum

On page 13 of Vol. 19 No. 3, the affiliation for the authors of the laboratory portrait on the Antiproton Decelerator at CERN was missing.
   Dieter Grzonka and Walter Oelert are both at:

   Forschungszentrum Jülich
   Institut für Kernphysik
   Jülich, Germany
High-Intensity Proton Accelerators

1. Au: tests or test as meant?
2. Au: please revise the phrase “the number of the hitting” for sense
3. Au: please revise “already exits as an electron storage ring” for sense
4. Au: Q-value than that?
5. Au: the sentence “Since the . . .” is a fragment; please revise
6. Au: please provide author affiliations
High-Intensity Proton Accelerators

Introduction

The construction of the J-PARC facility [1] was started in 2001 as a joint venture between KEK (High Energy Accelerator Research Organization) and JAERI (Japan Atomic Energy Research Institute, which was reorganized as JAEA (Japan Atomic Energy Agency) in 2005). The J-PARC facility is composed of a 400 MeV linac [2], a 3 GeV rapid cycling synchrotron (RCS) [3], and a 50 GeV synchrotron (MR, the beam energy is at present 30 GeV) [4], a materials and life science experimental facility, a hadron experimental facility, and a neutrino experimental facility as shown in Figure 1. The neutrino facility sends a neutrino beam to Super KAMIOKANDE. The beam commissioning to the beam lines planned at the first step had been successfully achieved as shown in Figure 2.

J-PARC is a multi-purpose facility, that is, it is not only a spallation neutron source, but also neutrino and kaon beam sources for high-energy and nuclear physics. It will be also used for commanding a basic study of an accelerator-driven nuclear waste transmutation system (ADS) in Phase II. The combination of LINAC and RCS has the advantage over that of LINAC and an accumulation ring (AR) as the spallation neutron source. The AR scheme needs a linac of full energy, but the RCS scheme permits a linac of low energy, because RCS accelerates a proton beam up to much higher energy than AR full energy. The RCS scheme reduces both the
linac construction cost and the beam current in large scale for the same beam power. It also reduces the beam loss power, because the injection energy is lower and the main loss occurs at the injection. But it raises hard problems of higher space charge effect in beam dynamics and of technical issues concerned with rapid cycling.

The other advantage of the RCS scheme is that it works as a suitable injector for a high energy synchrotron of a few tens GeV energy. The main purpose of MR is the production of high intensity secondary beams such as neutrino and kaon for high energy and nuclear physics.

The main operational goals of the J-PARC accelerators are summarized in Table 1.

### Linac

The linac scheme is shown in Figure 3. The volume-production type of the negative hydrogen ion source is used for producing a peak current of 50 mA with a pulse length of 0.5 ms and a repetition rate of 50 Hz. The beam is extracted at 50 keV to the 324 MHz radio-frequency quadrupole (RFQ) linac and accelerated to 3 MeV. Then, the beam is accelerated through the drift tube linac (DTL) to 50 MeV (shown in Figure 4), through the separated-type drift tube linac (SDTL) to 181 MeV, through the annular-ring coupled structure (ACS) linac to 400 MeV and through the super-conducting cavity (SCC) linac to 600 MeV according to the velocity increases. Here, SCC and ADS were shifted to Phase II. RFQ, DTL, and SDTL are operated with the same frequency by twenty 3-MW klystrons, which were newly developed by a klystron vendor for J-PARC in collaboration with the J-PARC accelerator team. This is preferable for longitudinal matching and stable operation. Transverse focusing is flexibly performed by electro-quadrupole magnets with water cooling, which are made by means of the electroforming technique and the wire-cutting. The high accelerating frequency and these magnets enable a short focusing period in both longitudinal and transverse directions, which is preferable for a high intensity beam.

The 181 MeV beam is injected to RCS at present and ACS is under construction for operation after a few years. The beam for RCS is chopped in order to avoid beam loss due to spilling from the RF bucket of RCS at injection. The main chopper is installed at MEBT1 in Figure 3, but this is not enough for the “perfect” rejection. (The extinction measurement was performed in MR and ~5.0E-5 of non-chopped beam was detected.) The pre-chopper installed between the ion source and the RFQ is necessary to increase quality. This is important to keep the residual radiation level at the RCS injection region low enough and realize empty buckets in RCS and MR for such an experiment as $\mu$-e conversion. The pre-chopper is an induction linac with the magnetic alloy (MA) cores since RFQ also works as an energy filter. However, this could not be operated before solving the problem that it works as a huge noise source when powered.

### RCS

The negative hydrogen beam is injected through the charge-exchange foil being converted to proton beam. This injection scheme is free from Liouville’s theorem, that is, a new beam can be put on the region of phase space already occupied by the circulating beam. Therefore, the beam density can be increased to the space charge limit in principle. To mitigate the space charge effect, the injection points in phase space are scanned to enlarge beam emittance in both the

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**Table 1. Main operation goals.**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Power (kW)</th>
<th>Repetition rate (Hz)</th>
<th>Energy (GeV)</th>
<th>Power (kW)</th>
<th>Repetition rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINAC</td>
<td>0.181</td>
<td>(30 mA)</td>
<td>0.4</td>
<td>(50 mA)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>RCS</td>
<td>3</td>
<td>600</td>
<td>3</td>
<td>1000</td>
<td>25</td>
</tr>
<tr>
<td>MR</td>
<td>30</td>
<td>300</td>
<td>30</td>
<td>750</td>
<td>~0.47</td>
</tr>
</tbody>
</table>

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**Figure 3. Scheme of J-PARC linac.**
transverse and the longitudinal phase space (so-called “Painting Process”). There were many issues to realize the advantage of the RCS scheme. The main items are as follows:

1. High accelerating voltage and wide frequency range of the RF acceleration system.
2. Ceramic vacuum chambers against large eddy current due to the fast change of magnetic field.
3. Large aperture magnets for the beam with large emittances to mitigate the space charge effect.
4. Magnetic field tracking in rapid cycle.
5. Injection and extraction system for the high intensity beam with large emittances.

**RF Acceleration System**

RCS accelerates proton beam from 181 MeV to 3 GeV with the repetition rate of 25 Hz in sinusoidal wave shape at present. The main parameters are summarized in Table 2. The maximum energy increment is about 240 GeV/sec and the minimum acceleration voltage is about 260 kV for zero emittance beam. For the acceleration with the acceptance enough for the high intensity beam, the maximum voltage is 450–500 kV. From Table 2 the required voltage per gap becomes about 16 kV because each cavity has three acceleration gaps and this needs the field gradient of about 30 kV/m in cavities. This value is two or three times of the conventional one made with ferrite cores. The high Q-value system is preferable to obtain effectively such a high gradient but it needs the exact and dynamic tuning of the resonance frequency of cavities according to the rapid acceleration. The magnetic alloy (MA) loaded cavity was adopted to overcome these problems. The Q-values are optimized as 2~10 by adding the external inductance or by adjusting the gap between the MA cores radially cut as seen in Figure 5. Each core is formed by winding MA ribbon (35 mm in width and 18 μm in thick) insulated with silica of 2 μm thickness. These cores have been newly developed and the manufacturing process has not been established yet. The ceaseless effort to improve the MA cores is necessary in parallel to the beam operation.

**Ceramic Vacuum Chamber**

All the vacuum chambers exposed to the fast varying magnetic field have been made of the alumina ceramics. Those for the quadrupole magnets (QMs) have the circular cross-section, which is relatively easy to manufacture except one QM located at the merging point of the injection beam in circulation. The cross-section of the race-track shape as seen in Figure 6. Each has the length of 3.5 m and consists of four parts; those are blazed with a tilt angle. The chambers for the injection region need large aperture and a special shape of cross-section as shown in Figures 7 and 8.

All the ceramic chambers have cupper stripes for RF shielding on the outside surface that makes smooth boundaries for the electromagnetic field generated by the beam. Each stripe has the width of 6 mm and the thickness of 1 mm and is connected to a titanium flange at one end through a capacitor to interrupt an eddy current circuit.

**Large Aperture Magnet**

In order to mitigate the space-charge defocusing effect, the QMs should have the large aperture, being short and close to the neighboring one for the frequent focusing. Then, the fringing field is not only quite strong but also interfered significantly with those of the neighbors. Together with

**Table 2. Present main parameters of RCS.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>348.333 m</td>
</tr>
<tr>
<td>Injection energy</td>
<td>181 MeV</td>
</tr>
<tr>
<td>Extraction@ energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Emittance at injection</td>
<td>&lt;324 π mm-mr.</td>
</tr>
<tr>
<td>Revolution frequency at injection</td>
<td>469.3 kHz</td>
</tr>
<tr>
<td>at extraction</td>
<td>835.9 kHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>25 Hz</td>
</tr>
<tr>
<td>RF frequency</td>
<td>(0.938---- &gt; 1.67) MHz</td>
</tr>
<tr>
<td>No. RF cavities</td>
<td>11 (---- &gt; 12)</td>
</tr>
<tr>
<td>Transition energy (γ&lt;sub&gt;T&lt;/sub&gt;)</td>
<td>9.14</td>
</tr>
<tr>
<td>No. BM</td>
<td>24</td>
</tr>
</tbody>
</table>
the saturation effects at the core ends, large higher multi-pole components might substantially reduce the dynamic aperture. Setting the distance between neighboring magnets suitable by careful consideration, no aperture reduction has been observed at present.

**Magnetic Field Tracking**

The QMs are driven by seven series-resonant circuit networks and the BMs are driven by a single parallel-resonant one. The IGBT-based power supplies are used since the fast switching is essential for the precise tracking of all the magnetic fields. However, the fast switching implies high-frequency components that can be easily coupled among the other networks through the incomplete grounding. It took almost one year for powering and controlling test in situ. Almost all the electromagnetic compatibility issues for BMs and QMs have been solved; those for the injection bump magnets and for the extraction kickers still remain unsolved. The in situ efforts have also been exerted to improve the signal-to-noise ratios of almost all the beam diagnostic systems by means of filtering the noises from the signals in addition to improving the electromagnetic compatibility. Anyway, all the electric circuits for the RCS at least should be treated as one circuit in total to achieve improvements.

**Injection and Extraction**

The injection and extraction devices have the large aperture, requiring large electric powers. These must have the fast rising and falling time. In particular, the decay of the magnetic field of the injection bump magnets should be faster than 100 μsec for the beam power of 1 MW, in order to reduce the number of the hitting of the circulating beams on the charge-exchange foil. The fast switching noise generates voltages larger than 400 V on the capacitors installed to the ceramics vacuum chamber. These capacitors will be replaced by ones that stand a voltage of 1.2 kV.

**MR**

There is transition energy in a conventional synchrotron. When the beam energy reaches this energy, the longitudinal focusing disappears in the first order and the line density of the beam blows up to infinity. Then, any instabilities and resultant beam loss occur. The MR lattice is so designed as to have imaginary transition energy being free from this situation. MR is the first proton synchrotron with this optics design, although there already exists as an electron storage ring for synchrotron radiation to enlarge tolerances against

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**Figure 5. Cut MA cores for MR.**

**Figure 6. Ceramic vacuum chamber for RCS bending magnets mounted with RF shield.**
The present main parameters are summarized in Table 3. The beam is accelerated to 30 GeV in 1.9 sec (2.5 sec at present) and extracted in one turn with the fast kickers to the neutrino production target, or extracted in the range of second with the controlled resonance of betatron oscillation (so-called Slow Extraction) to the hadron experimental facility.

The RF acceleration system is almost the same as that of RCS except for the following point. The MA cores were radially cut with a gap of 10 mm. The Q-value was thus optimized to about 10 in order to reduce the beam loading. The small change of frequency (1.67~1.72 MHz) permits larger Q-value that of RCS, still keeping the advantage of eliminating any tuning system.

**Beam Operation**

The J-PARC has good reproducibility regarding beam operation. After one or more days' interruption, a one-shot beam hits the same position on the hadron target through the slow extraction. This is nothing but the results of the stable operation of pulsed high-power devices, the transition free rings, the non-tuning RF cavities, and others.

RCS has been providing MLF with the beams for common use from December 2008, and the 20 kW beam is supplied constantly at present. The higher intensity operation was successfully demonstrated as 100 kW for 1 hour, 215 kW for 70 sec, and one shot corresponding to 320 kW if operated at 25 Hz. All these beam operations have been possible with the beam loss rate below designed for the real high-power operation. Since the present 320 kW beam power is equivalent to 1-MW in terms of the space-charge scaling law at the 400 MeV injection.

The biggest issue at present, however, is the discharge problem of the RFQ linac, preventing the beam operation from going beyond 20 kW. It is necessary to solve this problem for operating RCS with 20~100 kW. The key technologies regarding the space charge force to realize higher intensity than 100 kW are the RF cavity with the second harmonic and the precise tune control of betatron oscillation besides the painting process. The former keeps the beam length (or bunch length) as long as the longitudinal painting process makes, and reduces the tune spread due to space charge force by keeping the line density of beam as low as necessary.
Table 3. Present main parameters of MR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>1567.5 m</td>
</tr>
<tr>
<td>Injection energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Revolution frequency at injection</td>
<td>185.7 kHz</td>
</tr>
<tr>
<td>At extraction</td>
<td>191.2 kHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>~0.3 Hz</td>
</tr>
<tr>
<td>RF frequency</td>
<td>(167----&gt; 1.72) MHz</td>
</tr>
<tr>
<td>No. RF cavities</td>
<td>4(----&gt; 6)</td>
</tr>
<tr>
<td>Transition energy (γT)</td>
<td>31.7 i</td>
</tr>
<tr>
<td>No. BM</td>
<td>96</td>
</tr>
</tbody>
</table>

The latter helps the beam to avoid crossing of dangerous resonances. The chromaticity control is also necessary for correcting tune shifts arising from large momentum spread of high intensity beam.

MR had just passed the official inspection regarding radiation safety in January for hadron and May for neutrino. There are nine RF buckets, among which eight ones are used for beams to make the room of the rising time of kickers. However, the present kickers need longer rise time, resulting in only six buckets. The kickers will be replaced by new ones in one or two years. Although the achieved maximum beam power is about 3.5 kW at present, MR is ready to try 100 kW in 2009 and then 300 kW after some improvements of beam collimators and the repetition period of the power supplies for the BMs and QMs in a few years. The key technologies regarding the beam dynamics are here again the second harmonic RF cavity and the proper matching in both transverse and longitudinal plane between the RCS extraction and the MR injection. These are most effective to mitigate the space charge effect by keeping the reduced charge density.

We are now ready to go forward to obtain 600 kW for RCS and 300 kW for MR with 181 MeV linac in a few years, and then 1 MW for RCS and 750 kW for MR after upgrading linac energy to 400 MeV.

References
3. M. Kinsho, EPAC08, THXG02, pp. 2897–2901.
Hadron Experimental Hall

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On January 27, 2009, protons were accelerated by 50 GeV Proton Synchrotron (50 GeV-PS) up to 30 GeV, at which we will operate the PS at the first phase of the project, and successfully extracted to Hadron Experimental Hall in Nuclear and Particle Physics Facility and transported to the beam dump [1]. Hadron Experimental Hall is one of the two facilities at 50 GeV-PS and utilizes the various kinds of secondary particles generated by protons. To make plenty of secondary particles by the high intensity proton beam available for experiments, many methods of handling the high intensity beam have been developed for this facility. In particular, a firm radiation shield was constructed and magnets that were hard to break and easy to be replaced, in case of trouble in the high radiation area, were produced.

On February 10, after the careful tuning of the primary proton beam line, the secondary production target, T1, was inserted in the primary proton beam line and tuning of the secondary beam line started. The layout of the Hadron Experimental Hall is shown in Figures 1, 2, and 3. The beam extracted from 50 GeV-PS is transported along a 250 m Switch Yard (SY) and hit the T1 target placed at almost the upstream end (entrance area) of Hadron Experimental Hall, and is finally absorbed by the beam dump, which is located 50 m downstream from T1. Three secondary beam lines will be connected to the T1 target. The first is a K1.8 beam line that has two stage electrostatic (ES) separation and provides a very clean charged kaon beam up to 1.8 GeV/c. The second is K1.1. The configuration of K1.1 is almost the same as K1.8. However, the maximum beam momentum is 1.1 GeV/c and the beam length is much shorter than K1.8. Both K1.8 and K1.1 beam lines have their branch beam lines, K1.1BR and K1.8BR, after the first ES separator. The third beam line is a KL beam, which directly sees the T1 target and accepts a neutral kaon beam. This KL beam line is dedicatedly designed to the precise measurement of CP violating kaon decay in order to study the Cabibbo-Kobayashi-Maskawa matrix.

Last February, while the beam intensity of the first beam commissioning period was just 10 nA and the beam power of 300 W corresponding to 0.1% of the design, the joint experimental team, E17, led by Professor Ryugo Hayano, University of Tokyo and E15, led by...
Dr. Masahiko Iwasaki, Riken, successfully confirmed kaon generation in the secondary beams at K1.8BR, which was the only beam line available then, as shown in Figure 4. The beam line magnets of K1.8 BR were adjusted so that the beam momentum is held at 1.1 GeV/c, and the team obtained the clear signal of kaons in huge numbers of pions and secondary protons by means of the time-of-flight method. This result was reported by Dr. Takatoshi Suzuki, University of Tokyo, at the “Workshop Celebrating the First Beam at Hadron Hall” held on March 25–26 at Tokai [2]. The quantity of kaons is about 1/500 of that of pions, consistent with the expected value for un-separated beam condition without the operation of the electrostatic (ES) separator. The ES separator is designed to improve the kaon/pion yield ratio to be 1 or more. The actual ES Separator of K1.8 BR has already been installed in the beam line and tested in the working beam condition. This confirmation of the kaon generation is a big step forward to utilize the kaon beam at Hadron Experimental Hall.

The operation of the 50 GeV-PS for the fiscal year 2008 was terminated on February 26. We will continue constructing and tuning the other beam lines such as K1.8 and KL, which will be completed by autumn 2009. At K1.8BR, full installation of the E17 experiment will resume, preparing for the next operation phase, which will start this autumn at the earliest. The beam intensity of 50 GeV-PS will gradually be increased to its design value for the first phase of the project (i.e., 30 GeV-15 μA). The high-power proton beam will be applied to the intense production of kaons, pions, and many other unstable and/or rare elementary particles such as antiprotons, which will allow significant progress in both nuclear and particle physics. In this meaning the Hadron Experimental Hall will be the first real Kaon Factory [3] in the world. Spectroscopic studies of $s = -2$ hypernuclei and precise measurements of CP violation in neutral kaons are the two major subjects of the Hadron Experimental Hall. A beam line and analyzer system prepared for ($K^-, K^+$) reactions to produce $s = -2$ hypernuclei is now underway at K1.8 beam line as shown in Figure 5. The K1.1 BR beam line will be ready in the next Japanese fiscal year, 2010.

However, in the early days of J-PARC, on which the beam power is gradually increasing to the design value,
the experiments requiring relatively lower beam power are arranged to run. The search for $\theta^+$ by hadronic reaction ($\pi^-$, $K^-$) is one of the first series of such experiments at the Hadron Experimental Hall. Study of kaonic atoms using stopped $K^-$ is the other major subject of the early days. Study of vector meson’s mass modification in nuclear matter does not require the beam power but high momentum (>10 GeV/c) beam line, High-p, is necessary. Construction of this kind of high-p line is now seriously in consideration, as seen in Figure 2.

References
Strangeness Nuclear Physics at J-PARC

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From KEK PS to J-PARC

The old KEK proton synchrotron, which was shut down in 2005, had played an important role for the development of strangeness nuclear physics together with the BNL AGS since 1990s. Here, I would like to pick up several important achievements.

- **Success of \((\pi^+, K^-)\) spectroscopy with the SKS spectrometer.** From \(^{7}\text{Li}\) to \(^{208}\text{Pb}\), clean excitation spectra were obtained in a wide range of mass number resolving a number of \(\Lambda\) single-particle orbits in heavy systems and various core-excited states in light systems, for the first time [1]. This method was further applied to investigate the \(\Sigma\)-nucleus interaction and to produce neutron-rich \(\Lambda\) hypernuclei.

- **Success of hypernuclear gamma-ray spectroscopy with Hyperball.** A gamma-ray detector system consisting of 14 germanium crystals, called Hyperball, was constructed for hypernuclear spectroscopy with a great success to observe a lot of gamma-ray transitions in the \(p\)-shell \(\Lambda\) hypernuclei [1]. These observations revealed the peculiarities of the spin-dependent \(\Lambda\)-N interactions compared with the N-N case [2].

- **Success of hybrid-emulsion measurements to explore the \(S=-2\) systems.** The existence of double-\(\Lambda\) hypernuclei was established with new emulsion events. In particular, a \(^{6}\text{He}\) event, called “Nagara” event [3], was uniquely identified and its binding energy was precisely measured for the first time. Because of the limited beam intensity of \(K^-\) at KEK-PS, main experimental investigations were focused on the \(S=-1\) systems, \(\Lambda\) and \(\Sigma\) hypernuclei. On the contrary, the world-highest intensity beams of \(K^-\) will be available at J-PARC. They will enable us to fully explore the \(S=-2\) systems, \(\Xi\) hypernuclei, and double-\(\Lambda\) hypernuclei, in the \((K^-, K^+)\) spectroscopy, and much more abundantly produce the \(S=-1\) systems with the \((K^-, \pi^-)\) reactions than before (Figure 1).

A lot of experimental proposals have been submitted and considered by the Program Advisory Committee (PAC). Many of them are already approved to run. Among them, the following five experiments were categorized as “Day-1” experiments in the Hadron Experimental Hall by the PAC:

- E05: Spectroscopic Study of \(\Xi\)-Hypernucleus \(^{12}\text{Be}\), via the \(^{12}\text{C}(K^-, K^+)\) Reaction (T. Nagae),

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Figure 1. Three-dimensional hypernuclear chart with the strangeness (\(S\)) axis.

Figure 2. Setup of the SKS+ spectrometer for the \((K^-, K^+)\) spectroscopy. A dipole magnet is installed in front of the SKS spectrometer.
E13: Gamma-ray spectroscopy of light hypernuclei (H. Tamura),
E15: A search for deeply bound kaonic nuclear states by in-flight $^3$He(K$^-$, n) reaction (M. Iwasaki, T. Nagae),
E17: Precision spectroscopy of kaonic $^3$He 3d$\rightarrow$2p X-rays (R. S. Hayano, H. Outa),
E19: High-resolution Search for $\Theta^+$ Pentaquark in $\pi^- p \rightarrow K^- X$ Reaction (M. Naruki).

In this report, I would like to introduce three experiments, E05, E13, and E15.

**E05: Spectroscopic Study of $\Xi$ Hypernuclei**

Spectroscopic information on the $S = -2$ systems is very scarce at this moment. There are several emulsion events that confirm the existence of double-$\Lambda$ hypernuclei by observing sequential weak-decay patterns in emulsions. One of the events successfully measured the binding energy of $^{16}\Lambda\Lambda^4$He. There was a trial to identify double-$\Lambda$ hyperfragments by observing characteristic pionic weak decays in coincidence in a cylindrical detector system at BNL [4]. Such two-pion coincident events were observed. However the identification of the produced double-$\Lambda$ hyperframent was not conclusive.

As for $\Xi$ hypernuclei, there has been no conclusive evidence on its existence. Experimental information of the $\Xi$-N interaction is also very much limited. Therefore, there is no consensus whether $\Xi$ hypernuclei really exist or not, and how much would be the potential depth of $\Xi$ hypernuclei, if they existed. Nevertheless, it is believed that $\Xi$ hyperons would play an important role in the core of a neutron star in which high-density hadronic matter could be formed. In such high-density matter with the density more than a few times the normal nuclear matter density, neutrons in a neutron star would be converted to hyperons because of their large Fermi momentum. Negatively charged hyperon, $\Xi^-$, is also important to reduce the electron energy in the high-density matter.

In the J-PARC E05, a $\Xi$ hypernucleus, $^{12}\Xi$Be, will be looked for in the $^{12}$C(K$^-$, K$^+$) reaction at 1.8 GeV/c. The same reaction was used in the BNL E885 experiment [5]. In fact, they claimed to observe the evidence of $\Xi$ hypernucleus production. From the data analysis, the potential depth was estimated to be about 14 MeV for $A = 12$ when a Woods-Saxon type potential form was assumed. However, because of a poor energy-resolution they were not able to observe a peak or to determine the binding energy. In this experiment, the existing SKS spectrometer system will be modified for the (K$^-$, K$^+$) reaction (named SKS$^+$; Figure 2), and the expected energy resolution is better than 3 MeV (FWHM). Meanwhile, we will lose the solid angle acceptance from the original 100 msr (SKS) to 30 msr (SKS$^+$).

In the beam-line named K1.8, we also install a beam spectrometer system to measure the incident K$^-$ momentum particle by particle with the momentum resolution of $\Delta p/p = 1.4 \times 10^{-4}$. If we succeeded to observe a peak, not only the binding energy but also the conversion width

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**Figure 3.** Schematic view of the proposed Hyperball-J detector (lower half), and its prototype Ge detector equipped with a pulse-tube refrigerator.

**Figure 4.** A picture of the K1.8 BR area taken in February 2009. A cylindrical drift chamber (white) and a solenoid magnet (blue) are in preparation.
feature article

(Ξ p → ΛΛ) of the Ξ hypernucleus will be obtained in a good precision for the first time. An expected event rate is about 190 events/month with the beam intensity of $1.4 \times 10^6$ K$^-$/spill at 1.8 GeV/c.

E13: Gamma-Ray Spectroscopy of Light Hypernuclei

A new germanium detector Hyperball-J (Figure 3) is now in construction for the J-PARC E13 experiment. It consists of about thirty sets of Ge detectors having a photo-peak efficiency of about 75% relative to the 3$''$ × 3$''$ NaI detector. Each Ge detector is surrounded with fast PWO counters for background suppression. The photo-peak efficiency is expected to be better than 5% at 1 MeV at the distance of ~15 cm from a target.

The $(K^-\Xi^+, \pi^-)$ reaction at 1.5 GeV/c will be used to produce Λ hypernuclei at the K1.8 beam-line, as a Day-1 experiment. The SKS spectrometer will be used to tag the production of various Λ hypernuclear states in the $(K^-\Xi^+, \pi^-)$ missing-mass spectra. The SKS magnet should be excited at 2.7 T for the scattered pion momentum of ~1.4 GeV/c. The detectors at the exit of the SKS magnet will be enlarged to keep the solid angle acceptance greater than 100 msr. The maximum K$^-$ beam intensity would be $0.5 \times 10^6$ per spill at 1.5 GeV/c at the K1.8 beam-line.

A lot of interesting experimental subjects are proposed by using the Hyperball-J.

One of the important subjects is to measure the transition probabilities (B(M1)) of the Λ spin-flip M1 transitions, aiming to probe the g-factor of a Λ hyperon in a nucleus. A measurement of the M1(3/2$^-$→1/2$^+$) transition of $^7$Li seems to be promising. Considering the estimated lifetime of the 3/2$^-$ state ~0.5 ps, a Li$_2$O target with a density of 2.01 g/cm$^3$ in granular powder is selected to apply the Doppler-Shift Attenuation method.

Another interesting subject is an extension of hypernuclear gamma-ray spectroscopy in heavier systems. It is proposed to take the first data in the sd-shell region with a $^{19}$F target to detect both $^{19}$F (1/2$^-$$\rightarrow$3/2$^+$, 1/2$^+$) transitions in order to determine the ground-state doublet spacing.

E15: A Search for Deeply Bound Kaonic Nuclear States

The first experimental evidence for a $K^{pp}$ bound state was reported by the FINUDA group at DAΦNE in 2005 [6]. The Λ-p pairs emitted in back-to-back from the stopped $K^-$ absorption on $^6$Li, $^7$Li, and $^{12}$C targets were observed. The invariant mass of the Λ-p system was much smaller than the mass of the $K^-$+p+p system. Thus, it could be evidence that the $K^{pp}$ bound system is formed in the stopped $K^-$ absorption in the surface region of nuclei and decays into the Λ-p pair. Later, the mass shift of the Λ-p pairs has been confirmed in a new data set of much improved statistics by the FINUDA group. Further it is found that there is not such a large mass shift in the $K^-+p+n$ system decaying into Λ+n and Σ$^+$.p.

However, the reaction mechanism to produce such a deeply bound $K^{pp}$ system in the stopped $K^-$ absorption is not known well. Therefore, as for the interpretation of this mass shift, other interpretations [7] could not be excluded.

After the FINUDA observation, a lot of work to theoretically examine the existence of the $K^{pp}$ system has been carried out by using reliable few-body techniques [8]. All of these calculations have confirmed that the $K^{pp}$ bound state must exist with the binding energy of 20 to 70 MeV depending on the KN interaction models used in the calculations.

Therefore, it is of vital importance to experimentally confirm the existence of the $K^{pp}$ bound state. In the J-PARC E15, the in-flight (K$^-$, n) reaction on $^3$He at 1 GeV/c will be used to directly produce the $K^{pp}$ system. At this incident momentum, the elementary cross-section of K$^-n \rightarrow nK^-$ has a broad maximum of ~5 mb/sr. The neutron momentum emitted in the forward direction is measured with a time-of-flight counter wall. The $K^{pp}$ mass is measured as a missing-mass. At the same time, the target region is covered by a cylindrical detector system with a large acceptance, which is installed in a solenoidal magnetic field (Figure 4). Thus, most of the charged particles produced in the decay of the $K^{pp}$ system are detected. Here, the mass of the $K^{pp}$ system is measured as an invariant mass of the Λ+p pair. The designed missing-mass resolution is about 28 MeV (FWHM) with a flight path of ~12 m, and the invariant-mass resolution is about 40 MeV (FWHM).

Other Experiments

There remain a lot of experiments already approved by the PAC. They include Ξ-atom X-ray measurement, E03 (K. Tanida), a hybrid-emulsion experiment, E07 (K. Imai, K. Nakazawa, H. Tamura), neutron-rich Λ hypernuclei spectroscopy, E10 (A. Sakaguchi, T. Fukuda), and experiments of weak decay of Λ hypernuclei, E18(H. Bhang, H. Outa, H. Park) and E22 (S. Ajimura, A. Sakaguchi).
Summary

After the successful secondary beam production at the K1.8 BR beam-line in February 2009, we expect the next beam in the fall of 2009 at the K1.8 beam-line. Construction of new detector systems such as SKS+ for E05, Hyperball-J for E13, and a cylindrical detector system for E15, is now in rapid progress to prepare for the beams.

References
In the hadron hall, there are proposals to explore a broad range of physics, as follows:

1. Studies of hadron properties in the nuclear medium and searches for exotic hadrons
2. Kaon decay experiments to study CP and T violations
3. Muon precision physics

In this article, I describe the experimental program at hadron hall. A plan view of the hadron hall is displayed in Figure 2. It should be noted that a more detailed plan is being discussed to accommodate newly approved experiments.

Hadron Physics

In the low energy quantum chromo-dynamics (QCD) studies, the most important issue is the understanding of the quark confinement. More specifically, the questions would be:

- how the hadron properties emerges from the confinement;
- how those properties would change with respect to the temperature and density;
- how the confinement pattern is determined.

Hadron properties such as their mass and spin are the results of the quark confinement. In the process of confinement, non-trivial properties of hadron emerge. For example, hadron mass is explained as results of quark-anti-quark condensates that dynamically produces the hadron mass. The quark mass from Higgs mechanism is only a small fraction of the hadron mass and its dominant fraction is dynamically produced. Figure 2 displays such invariant mass spectra around $\phi$ mass region for carbon and copper targets.

Consequently the hadron mass could be modified in the nuclear medium, where the color field is rich. Indeed, such a modification was predicted by Hatsuda and Lee back in 1992 [1]. Furthermore, experimental signature is observed by experiment KEK-PS E325 [2]. In the invariant mass

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**Figure 1.** A plan of the hadron hall. A more detailed plan is being discussed to accommodate newly approved experiments.
spectra of di-electrons from the proton–nucleus collisions at 12 GeV, some excess in the lower mass region around the $\rho$, $\omega$, and $\phi$ vector mesons were reported. Clearly, further clarification is necessary, especially to understand the modification mechanism. There is a proposal to accumulate larger statistics than E325 by two orders of magnitude with improved detector system [3]. The proposal received the scientific approval, and the beam-line construction is planned in a few years.

As a part of the QCD studies, searches for exotic hadron states will be performed. One of the Day-1 experiments at the hadron hall would be a search for the penta-quark state, $\Theta^+$ in $\pi^{-}/K^{-}$ reaction [4]. There is a letter of intent to perform a resonance search in reaction, where one would expect $s$-channel formation of $\Theta^+$ state. We hope the situation will be clarified with these measurements.

There are several other proposals focused on the hadron studies including Drell-Yan experiment at 50 GeV. Currently the Main Ring is constructed with 30 GeV capability, and the initial phase optimization will be done for 30 GeV. There is a plan to pursue this physics at Fermilab using 120 GeV proton beam [5]. They also plan to move the spectrometer from Fermilab to J-PARC once the 50 GeV is realized.

**Kaon Rare Decay Experiments**

Since the first discovery of the $CP$ violating process in the neutral kaon decays back in 1964, the kaon decay experiments have played the central role in understanding the $CP$ violation in the quark sector. The process yielded the concept of the quark mixing and led to the discovery of the three generations of quarks and leptons in the standard model.

Among several decay processes in kaons and B-mesons, the decay channel has been waited eagerly for many years, since the decay occurs via direct $CP$ violation through the loop diagrams.

A pilot experiment, called E391a, has been done at KEK-PS. The measurement was performed with a pencil beam of neutral particles at the production angle of 4 degrees. The experiment set the upper limit of the branching ratio of the process at $6.7 \times 10^{-8}$ at 90% confidence level [6].

While the final results from the E391a are yet to be released, it is clear that further exploration is irreducible to complete the picture of the flavor mixing and $CP$ violation in the quark sector.

The experiment E14(KOTO) [7] is, as the first step, proposed to reach the standard model prediction, which is $\sim 10^{-11}$. The experiment received a full approval recently. The experiment is preparing for the first beam test especially to investigate the yield of neutral kaon beam, which is the key of the experiment. The experimental layout is shown in Figure 3.

**A Search for Violation of Time Reversal Invariance**

Once the CPT theorem is assumed to be valid, time reversal invariance should be violated as a result of $CP$ violation. Indeed $T$ violation is observed in $K^0-\bar{K}^0$ oscillations.
There have been longstanding efforts to discover T violations beyond the standard model. Main investigation has been done in searches for electric dipole moment, either in atomic systems, or neutrons, as well as charged leptons. A unique search was performed at KEK-PS using $K^+\rightarrow \pi^0\mu^+\nu_\mu (K_{\mu3})$ decay channel by searching for the transverse polarization of muon ($P_T$) in the decay plane. The standard model prediction for $P_T$ through CKM matrix element $V_{us}$ is essentially zero, and estimated to be less than $10^{-7}$. Unlike the beta decays in nuclei, an effect of final state interaction (FSI) is also reasonably small at the level of $10^{-5}$. Therefore, any signal in the current search range ($10^{-3}-10^{-1}$) would directly imply the existence of new physics. Indeed, some of the new physics models such as multi Higgs-doublets model expect the size of $|P_T|$ as large as $10^{-3}$.

The E246 at KEK-PS has constrained $|P_T|$ to be less than $5\times10^{-4}$ at 90% confidence level. The new experiment E06 (TREK) is planning to improve the precision down to $\sim1\times10^{-4}$. While the experiment is waiting for funding to start the construction, the beam-line construction is underway.

**Muon Precision Physics**

A flavor mixing observed in the quark sector led to successful description of CP violating processes in the quark sector. In the lepton sector, a large mixing is observed in the neutrino sector. There is, however, no mixing observed in the charged lepton sector. Given the large mixing in the neutrino sector, we can expect finite mixing in the charged lepton flavor even within the framework of the Standard Model (e.g., $\mu \rightarrow e\gamma$) through neutrino mixing. Such branching ratio is estimated to be $\sim10^{-50}$, which is out of reach of a current experimental technique.

In the presence of new physics such as supersymmetry, however, the branch would become as large as $10^{-13}$, which is still within reach. Therefore, any observation of the charged-lepton-flavor-violating (cLFV) process will be stunning evidence of new physics and thus searches for cLFV processes have been performed for many years, using various processes. Current direct limit is obtained from MEGA experiment at Los Alamos to be $<1.2\times10^{-11}$ at 90% confidence level [8]. Recently the MEG experiment at Paul Scherrer Institute has obtained the first result to be $<3\times10^{-11}$ at 90% confidence level. The experiment will continue to search for the process in the coming few years [9].

A cLFV process is also searched for in muonic atoms. When negatively charged muons stop in matter, they quickly form an atomic bound state. While most of the muons would decay in orbit, a possible $\mu-e$ conversion would provide mono-energetic electrons with an energy of muon mass minus binding energy of a muon by the nuclei. Such a signal has been searched for by the SINDRUM II experiment at PSI with several nuclei. The most recent result was obtained to be $<7\times10^{-13}$ at 90% confidence level for $\mu^-\text{Au} \rightarrow e^-\text{Au}$ [10].

At J-PARC, cLFV searches in $\mu-e$ conversion are proposed in two stages. A high sensitivity search at the level of $10^{-18}$ was proposed as the PRISM/PRIME experiment [11]. Recently the COMET experiment is proposed to aim for $10^{-16}$, which can be connected to PRISM/PRIME efforts. The experiment received the scientific approval from the PAC and the details of the experiment are explored by the collaboration and the special task force formed in KEK. The task force has started the development of key technologies such as an improvement of beam extinction with accelerator group.

There is a similar experiment proposed at Fermilab, called mu2e. Since the sensitivity and the time scale is very similar in both efforts, collaborative activities are being explored.

In addition to these cLFV experiments, there is a proposal for precision measurement of the anomalous magnetic moment of muon. The most recent results from Brookhaven National Lab (BNL) experiment E821 exhibits more than three standard deviations from the standard model prediction [12]. It is considered to be a hint for a new physics, and further exploration is necessary.

The experiment E821 was a successor of the CERN measurement back in the early 1980s. The measurement
utilizes the tertiary muon beam stored in the muon storage ring with uniform magnetic field at a level of 0.17 ppm. Since uniform magnetic field cannot provide a focusing of the muon beam, electric quadrupole filed was used to keep the beam in the storage ring.

In the presence of the magnetic and electric field, the precession frequency of the magnetic moment relative to the momentum direction is expressed as

$$\omega_a = \frac{e}{m} \left[ a_m B - \left( \frac{1}{\gamma^2 - 1} \right) \frac{\beta \times E}{e} \right]$$

where $a_m$ is the anomalous magnetic moment of muon. To eliminate the rotation due to electric field, the coefficient in the second term is set to zero in the previous experiments. This can be done by choosing the $\gamma$ value to be 29.3, which corresponds to muon momentum of 3.09 GeV/c.

A part of the collaboration from the BNL experiment is proposing an improved measurement at Fermilab by moving the muon storage ring from BNL. They aim to improve the precision by a factor of 5 to reach 0.1 ppm precision [13].

There is another effort being explored at J-PARC. The experiment is proposed to utilize the ultra-cold muon beam with “table top” storage ring. The ultra-cold beam can circulate in the storage ring without focusing field. Such a beam can be produced from ultra-slow muon source, which is demonstrated in the RAL-ISIS facility [14]. The “table top” storage ring is of ~0.7 m diameter, which is significantly smaller than the BNL muon ring, which has 14 m diameter.

Such a small magnet can be precisely adjusted thanks to the development in MRI technology. A letter of intent for such a measurement is submitted and the collaboration is preparing the full proposal, setting the goal to reach 0.1 ppm precision. Since the proposed experiment utilizes a novel technique, experimental systematics would be completely different from the previous experiment. Such an independent measurement will be irredicible in exploring the precision frontier of muon science.

Acknowledgment

The author thanks Professors Komatsubara, Mihara, and Takahashi for their useful comments on this article.

References

The T2K Experiment

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The Goals of T2K

Over the last dozen years neutrino physics has crossed a threshold in its basic understanding of the fundamental nature of neutrinos. The first compelling demonstration that neutrinos have mass came when the Super-Kamiokande experiment showed a zenith-angle dependent suppression of muon neutrinos arising from cosmic ray interactions with the atmosphere. That had already been suspected, because initial indications of an anomaly in the flux of neutrinos from the sun from the pioneering experiments of Ray Davis and his collaborators and from the Kamiokande experiment, supported by measurements of the low-energy solar neutrino fluxes by the SAGE and GALLEX experiments, were hard to explain without invoking new neutrino physics. The SNO experiment then demonstrated that the shortfall of solar neutrino was caused by neutrino coming from the sun changing flavor, further pointing to the existence of neutrino oscillations. This was confirmed by the observation (or rather non-observation!) of the disappearance of reactor neutrinos by the KamLAND experiment and of accelerator neutrinos by the K2K long-baseline neutrino oscillation experiment (subsequently confirmed by the MINOS experiment). The combination of all these experimental results clearly demonstrates the existence of neutrino oscillations (the first confirmed physics beyond the Standard Model of particle physics).

Neutrino oscillations arise quite naturally in a model whereby the weak eigenstates of the neutrinos \( \nu_i \) are a mixture of the mass eigenstates \( \nu_i \):

\[
|\nu_i\rangle = \sum_j U_{ij} |\nu_j\rangle
\]

The matrix \( U_{ij} \) is called the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) mixing matrix. It is analogous to the CKM matrix, which mixes the weak and strong eigenstates of the quarks, and can be written for the case of three Dirac neutrinos (in an analogous way to the CKM matrix):

\[
U_{ij} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} \\
0 & 1 & 0 \\
0 & e^{i\theta} & -s_{13} \end{pmatrix}
\]

where \( c_{ij} = \cos \theta_{ij} \) and \( s_{ij} = \sin \theta_{ij} \).

The matrix \( U_{ij} \) parameterize the three possible rotations between the neutrino states. Pure \( \nu_i \) states are emitted in weak interactions, but what propagate are the \( \nu_i \) states. If the masses of the \( \nu_i \) are different they will build up a relative phase difference, and therefore when their superposition is decomposed back into the \( \nu_j \) states an admixture of a “wrong” flavor (i.e., a flavor not emitted in the weak interaction that created the neutrino) appears—the phenomenon we call neutrino oscillations. For the simplest case, where only two of the mass states dominate the oscillations, the familiar formula that governs the appearance of one flavor, say \( \nu_e \), in an initially pure beam of another flavor, say \( \nu_{\mu} \), can be derived:

\[
P(\nu_{\mu} \to \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})
\]

where \( \theta \) is whichever of the angles is contributing to this particular mixing, \( L \) is the distance from the source to the

Figure 1. The rebuilt Super Kamiokande detector during refilling. Each phototube is 50 cm in diameter. Note the two men in a boat.
detector, \( E \) is the energy of the neutrino, and \( \Delta m^2 = m_1^2 - m_2^2 \) is the difference in the squares of the masses of the two \( \nu_i \) states which are mixing. The numerical constant 1.27 is valid for \( L \) in meters, \( E \) in MeV, and \( \Delta m^2 \) in eV\(^2\). Note that these oscillations depend only on \( |\Delta m^2| \), that is, they do not depend on either the absolute mass scale or ordering of the mass states. This formula is valid in vacuum, however interactions with electrons in matter can modify the oscillations (the MSW effect) leading to their enhancement (or suppression). These matter effects do depend on the sign of \( \Delta m^2 \), and thereby provide a way to determine the ordering of the mass states (although not the absolute masses).

The goal of experimentalists is to demonstrate, understand, and eventually explain the origin of the MNSP matrix. Of the 8 effective parameters which control oscillations (the 3 angles, the two independent mass-squared differences between the masses of the mass eigenstates, the signs of these two mass differences, and the CP-violating phase) existing experiments have only determined 5 so far. So one priority must be to determine the remaining 3 (the value of \( \theta_{13} \), the sign of \( \Delta m_{23}^2 \), and \( \delta \)). The eventual main target is \( \delta \), as this would give a window into CP violation in the neutrino sector, which may hold the answer to one of the greatest mysteries in fundamental physics today—where did the matter in the universe come from? Since the effects of \( \delta \) in oscillations always appear multiplied by \( \sin^2 2\theta_{13} \), finding a non-zero value for \( \theta_{13} \) is a critical step in the campaign to measure \( \delta \). However, one should also not forget that we are not just filling out tables of numbers for the sake of completeness, but are trying to understand the underlying physics which generates neutrino mixing. Right now we know that of the three neutrino mixing angles, two are “large,” and one is “small”; however, the uncertainties are still large and in fact within existing errors the three numbers look very much like three random numbers in the allowed range (and hence carry little useful information about the underlying physics). However if the errors could be reduced we might find that we were seeing “special” numbers, that is, a \( \theta_{13} \) very close to zero or \( \theta_{23} \) very close to maximal, which should be pointing to some underlying symmetry that a more fundamental theory must explain. So this suggests a two-fold measurement programme to better determine the already observed quantities and to get first measurements of the unknown ones, and to both these efforts the measurement of \( \theta_{13} \) is critical.

The T2K experiment is designed to be a major step forward on both fronts. It was created to take advantage of two facilities that would be available in Japan—the Super Kamiokande detector and the J-PARC accelerators. The basic idea is the same as most previous long-baseline neutrino oscillation experiments such as the K2K experiments (which aimed a beam of neutrinos derived from the PS at KEK toward Super Kamiokande), and indeed as most accelerator neutrino experiments dating back to the first neutrino horn at CERN in the early 1960s. The proton beam from the main synchrotron at J-PARC will be
collided with a target to produce intense bursts of pions. These pions are collected and focussed forward by a magnet system consisting of 3 “horns” (selecting one charge, usually positive, in the process) into a decay volume. The resulting pion decays produce beams of $\nu_\mu$ and muons, and the decay volume length is adjusted so that most of the pions but as few of the muons as possible decay before they reach the beam dump at the end. The properties of the resulting neutrino beam are measured by a system of near detectors at J-PARC, and the beam then propagates through the ground underneath nearly the width of Japan before reaching the Super Kamiokande detector. The Super Kamiokande detector consists of an enormous right circular cylinder (40 m in diameter and 40 m high) filled with ultra-pure water in which are suspended 11,000 photomultipliers which, despite their large size (50 cm diameter), are sensitive enough to detect single photons (see Figure 1). Surviving $\nu_\mu$ and any $\nu_e$ they have oscillated into can undergo charged-current quasi-elastic (CCQE) interactions with the nuclei in the water and produce charged muons and electrons that retain most of the energy of the incoming neutrinos (the beam energy at T2K is too low for $\nu_\tau$ produced by oscillations to undergo CCQE interactions, as it is below threshold for $\tau$ production). The resulting muons and electrons are relativistic and therefore emit Cerenkov radiation in the water, which is detected by the phototubes. The total amount of light produced gives a measurement of the particle’s energy, while the positions and times hits on the phototubes allow its position and direction to be reconstructed as well. Furthermore, muons tend to travel in fairly straight tracks, while electrons scatter and shower in the water, producing distinct hit patterns that can, with quite high accuracy, distinguish muons from electrons and hence $\nu_\mu$ from $\nu_e$.

The properties of both the accelerator and the detector are very well matched to the needs of a next-generation oscillation experiment. The distance between these two facilities (295 km) is such that the peak of the oscillation for the atmospheric neutrino oscillation would occur at ~600 MeV, quite close to the peak cross section of $\nu_\mu$ charged-current quasi-elastic (CCQE) scattering—pretty much the ideal energy for measuring $\nu_\mu$ disappearance. At these energies neutrino interactions are relatively simple, with few particles in the final state. Such final states are well-reconstructed in water Cerenkov detectors like Super Kamiokande, allowing advantage to be taken of its huge size (50 kton total mass). The J-PARC facility is designed to reach the highest average beam power of any pulsed proton beam, which is another critical parameter for maximizing the event rate and hence sensitivity in a long-baseline neutrino experiment.

Figure 4. Neutrino spectrum for various off-axis angles in degrees.

Figure 5. The INGRID on-axis neutrino detector configuration. Each box is a roughly 1m$^3$ iron-scintillator tracking detector as described in the text and shown in the inset image. The intersection of the vertical and horizontal detector arrays is centered on the beam direction, with the signals in the detectors allowing the beam profile and direction to be precisely determined.
Critical Issues for T2K Oscillation Measurements

T2K will make two related measurements of oscillations of the $\nu_\mu$ beam aimed at the two different measurement programs discussed earlier. The first of these will look at the disappearance of the $\nu_\mu$ beam by observing muons from CCQE reactions from the surviving beam. For the parameters of T2K this oscillation is absolutely dominated by the "atmospheric" oscillation, and therefore its measurement will allow the accurate determination of the values of $\sin^2 2\theta_{23}$ and $\Delta m_{32}^2$. The critical issues for this measurement are:

- The energy spectrum of the $\nu_\mu$ beam before any oscillations take place must be accurately known. Oscillations produce a "dip" in the energy spectrum (see Figure 2), and in principle the depth of this dip directly determines $\sin^2 2\theta_{23}$ and its position in energy determines $\Delta m_{32}^2$. However, this dip is superposed on an unoscillated spectrum that (for reasons that will be discussed shortly) is quite strongly peaked in energy, so this unoscillated spectrum must be known with considerable precision before the actual properties of the dip can be inferred from the observed spectrum after oscillations.

- A second problem is also shown in Figure 2, which is that the events reconstructed as CCQE muons in Super Kamiokande are not purely from CCQE interactions, but may arise from other, more complex, interactions. There may be other particles in these events that are missed, either because they are neutral and therefore do not emit Cerenkov radiation or because they are below Cerenkov threshold (and occasionally pions are mistaken for muons). Most of these events are rejected during analysis, but a few sneak through and produce a non-CCQE background where the energy of the reconstructed "muon" is not cleanly related to the energy of the neutrino. The effect of this is to fill in and shift the

Figure 6. The 280 m Off-Axis detector layout. The various detector elements are described in the text. The magnet yokes and coils have been omitted from the side nearer the viewer so that the other elements are visible. The thin slots in the yokes in which the SMRD scintillators are inserted are also visible.

Figure 7. Hit patterns for three event types in Super Kamiokande. On the far left is a muon, showing the clearly defined ring structure. In the middle is an electron, showing the fuzzier ring caused by showering. The far right event is from a $\pi^0$, and a second ring can be seen on the right edge of the main ring. Each colored square indicates a hit photomultiplier, with the size of the square showing the amount of charge in the phototube and the color the relative timing.
dip in the spectrum, so the effects of non-CCQE events must be well understood before reliable oscillation parameters can be extracted from the data.

- Part of the problem of understanding these non-CCQE backgrounds is that exclusive cross-sections (the probabilities of each specific type of interaction, a charged-current interaction with the production of one additional pion from the vertex, called CC1π, for instance) for neutrino interactions in this energy range are very poorly known, so it is difficult to predict from simulations the exact nature of the CCQE background.

- As the position of the dip in energy gives the value of $\delta m_{23}^2$, the energy calibration of all detectors (in particular Super Kamiokande) must be well understood.

Figure 8. Sensitivity limit for detecting electron neutrino appearance as a function of the systematic error on the backgrounds. Note the variation in sensitivity with CP phase, which is bad (as it lessens the sensitivity to $\theta_{13}$ for some values of $\delta$), however also good, as it shows that for $\theta_{13}$ within the sensitivity range of T2K there are effects due to $\delta$ that could be demonstrated by an upgraded experiment.

The second T2K oscillation measurement is to look for appearance of $\nu_e$ in the $\nu_\mu$ beam. If $\theta_{13} = 0^o$, then the $\nu_\mu$ would oscillate to $\nu_e$ and we would see no $\nu_e$ in the beam (ignoring a tiny contribution from the oscillations that produce the solar neutrino deficit, which are negligible at the energy and baseline of T2K). However if $\theta_{13} \neq 0^o$, there is a sub-leading oscillation that does produce $\nu_e$ in the beam, and hence an observation of these $\nu_e$ (via the observation of the electrons produced by their CCQE interactions) would allow a measurement of $\theta_{13}$. The issues here are (see Figure 3):

- Even before oscillations, there is a small contamination of $\nu_e$ in the $\nu_\mu$ beam that arises primarily from the decay of $K_s$ produced at the same time as the $\pi^0$s, and from the decay of the $\mu$ before they can be stopped. This contamination must be accurately determined so that its effects can be subtracted when looking for $\nu_e$s from oscillations.

- Any neutrino, oscillated or not, can interact with the target via neutral current interactions. One type of products of these interactions are neutral pions. These $\pi^0$s decay immediately into two gamma rays, which shower within the detector. If the decay is highly asymmetric, and one of the gamma rays has very low energy, it might be missed, resulting in detection of a single gamma ray shower that looks very much like the single electron seen in CCQE events. This produces a background to the $\nu_e$ oscillation search, and therefore it is necessary to understand in detail the production of these $\pi^0$s and to minimize their number by eliminating any neutrinos from the beam that are not near the oscillation maximum (that contribute to this background, but not to the signal).

- Sensitivity to the smallest values of $\theta_{13}$ is primarily limited by statistics and by systematic uncertainties in determining the above backgrounds. We therefore need the most intense beam possible, and need to quantify the backgrounds as precisely as possible.

The combination of these issues has strongly driven the design of the T2K experiment, resulting in decisions to adopt an off-axis geometry (with, of course, the highest proton intensity available) and a complicated suite of detectors 280 m from the target to understand the beam and its interactions in detail before it has time to oscillate.

The Beam-Line and Off-Axis Geometry

Due to space constraints on the J-PARC site, the proton beam-line for the T2K beam has to be bent in a tight radius inside the MR. This requires the use of dual-function (dipole and quadrupole) superconducting magnets. Once the proton beam is pointing in the right direction, which in addition to the beam-line itself requires a complicated system of monitors to determine the position and direction of the beam at each point, the next step is to collide it with the pion production target, which is a 90 cm long graphite rod cooled by high-pressure He gas flow. In order to maximize the pion collection efficiency the target is actually located inside the first horn magnet. To get a feel for the challenge, note that if single pulse of the 0.75 MW beam hit a solid iron block it would raise the internal temperature of the block to 1100°C and produce stresses exceeding the tensile strength of the material. The target must be able to survive such pulses every few seconds for roughly 1/3 of the year without failing, it must have very little material around it so that
the pions can escape and be efficiently collected, and it must not interfere with the horn magnet that surrounds it. Of course the targets and horns will become very heavily radioactive after even brief operation, so any maintenance/repair activities will have to be conducted remotely, and any damaged/discarded targets will have to be stored as high-level waste.

The pions exit the horns into a ~80 m long He-filled decay volume where the neutrinos are produced. At the end of this decay volume is the beam dump, where any undecayed pions, the lower energy muons from the pion decays, and the remaining proton beam are stopped (this amounts to about one quarter of the total initial proton beam power). This beam dump is also an engineering challenge, as it will also become highly active and cannot be altered or replaced once the beam begins operations. It has therefore being designed to handle the largest power planned for future upgrades of the J-PARC/T2K facility, which is 4 MW average beam power. Behind the dump is a set of detectors to measure the position and direction of muons from the high-energy tail of the beam. Looking at these muons enables the operators to monitor on a spill-by-spill basis the position and direction of the beam, insuring that it is aimed properly with respect to Super Kamiokande.

Most of this equipment got its first beam test on April 23, 2009, when the first shots of the proton beam were delivered from the MR. We were extremely pleased when the very first shot of the proton beam was steered around the beam-line and into the target facility and produced a detectable signal in the muon monitors. After just 9 shots the beam had been centered on the target, and subsequent measurements showed all installed elements to be working well. As of the time of this writing we are now engaging in the final installation and preparation for the next running of the beam in October/November 2009, with oscillation data-taking scheduled to begin in December/January.

But what is the right direction to aim the beam? A key element of the design of the T2K facility is that the neutrino beam is very carefully pointed so that the beam axis actually misses Super Kamiokande. This, rather surprisingly, actually results in a considerable improvement in the quality of the beam for the $\nu_e$ appearance experiment. This arises from the kinematics of $\pi$ decay, which result in an enhancement in the neutrino flux produced over a very narrow range of energies that depend on the exact off-axis angle (see Figure 4). If the angle is carefully selected this narrow peak can be put exactly on the oscillation maximum at the far detector. This has three major advantages over a conventional on-axis beam. Firstly, the off-axis neutrino flux at the desired energy (the oscillation maximum) is actually higher than on-axis. Secondly, there are fewer high-energy neutrinos, which do not contribute to the appearance signal but do contribute to its backgrounds, in particular through the neutral-current production of $\pi^0$s. Thirdly, the background due to the intrinsic contamination of the beam by $\nu_e$ is actually less at the off-axis position due to the different kinematics of the decays that lead to $\nu_e$.

The off-axis position therefore has great advantages; however, the very kinematics that give a useful selection in energy mean that the characteristics of the beam change rapidly with angle. Our detectors at 280 m are near enough to the beam-line that it sees the beam-line over an appreciable range of angles, so it seems a different neutrino spectrum than Super Kamiokande. This “near/far” effect needs to be corrected for to extrapolate a measurement of the neutrino spectrum at JPARC to the expected spectrum at Kamioka, which requires a detailed understanding of the kinematics of the pions in the beam. The relevant pion (and kaon) production cross-sections are being measured in a dedicated experiment at CERN (NA61), without which T2K’s precision would be limited by this effect.

The 280 m Detectors

The 280 m detector complex will contain two detectors, the on-axis detector INGRID and the off-axis detector. The purpose of the former is to determine the neutrino beam profile and direction, while the latter will measure the beam spectrum, make measurements of neutrino interactions (including the problematic $\nu^-$s), and determine the intrinsic $\nu_e$ contamination of the beam.

INGRID

The INGRID detector consists of an array of iron-scintillator tracking modules (see Figure 5). Each module is roughly a 1 meter cube consisting of ten 1 m × 1 m plates of 10 cm thick iron separated by layers of plastic scintillator strips. In each strip is embedded a wave-length shifting optical fiber, which captures the light and channels it out to a Hamamatsu MPPC on the end of the strip. The modules are designed to have extremely high efficiency for the detection of CCQE muons (>99%), where each muon will appear as a line of hit strips in different planes. The relative muon rates in the different modules will be used to reconstruct the beam profile and direction, where the goal is to measure the direction to 0.06° per day.

This scintillator/fiber/MPPC technique is in fact used in all of the subdetectors at 280 m (except for the TPCs). The MPPC, or Multi-Pixel Photon Counter, is a new type of photosensor that will see its first large-scale use in T2K. Each MPPC is an array of small APD pixels run in Geiger mode. When a pixel is hit by a photon it produces a saturation avalanche of fixed size, which when summed together gives a signal that
basically just counts the number of photons detected. MPPCs have many advantages over photomultipliers. They are small, fast, cheap, have high quantum efficiency, will run at only 70 V, and will work in kG magnetic fields. A few drawbacks arise from the use of such high gain within each pixel—the single-pixel noise rate is very high (hundreds of kHz), so that a threshold is required at a few pixels to keep the rate manageable, and the gains of the devices are a strong function of temperature, requiring cooling and continual calibration.

The 280 m Off-Axis Detector—ND280

The ND280 detector will sit on the line between the mean pion decay position in the beam and Super Kamiokande, where it gives the best approximation of the beam distribution as seen at Super Kamiokande. A schematic view of the detector is shown in Figure 6. It is surrounded by the UA1/NOMAD magnet (kindly donated to the experiment by CERN), which provides the ~0.2 T magnetic field used to determine the momentum of CCQE muons. The central part of the detector consists of two sections with different capabilities:

1. The Pi-Zero Detector, or P0D, sits at the upstream end of ND280m, and is optimized for measuring the rate of neutral current $\pi^0$ production. The P0D consists of tracking planes composed of scintillating bars alternating with lead foil. Inactive layers of passive water in sections of the P0D also provide a water target for measuring interactions on oxygen.
2. Tracker: Downstream of the P0D is a tracking detector optimized for measuring the momenta of charged particles, particularly muons and pions produced by CC interactions, and for measuring the $\nu_e$ background in the beam. The tracker consists of two detector technologies, Time Projection Chambers (TPCs) and Fine Grained Detectors (FGDs):

- Time Projection Chambers: Three TPCs will measure the 3-momenta of muons produced by interactions in the detector, and thus provide the most accurate measurement of the neutrino energy spectrum. The 3D tracking and dE/dx measurements in the TPC will also determine the sign of charged particles and identify muons, pions, and electrons.
- Fine Grain Detectors: Two FGD modules, placed after the first and second TPCs, consist of layers of finely segmented scintillating tracker bars. The FGDs provide the target mass for neutrino interactions that will be measured by the TPCs, and also measure the direction and ranges of recoil protons produced by CC interactions in the FGDs, giving clean identification of CCQE and CC non-QE interactions. One FGD module will consist entirely of plastic scintillator, while the second will consist of plastic scintillator and water to allow the separate determination of exclusive neutrino cross-sections on carbon and on water.

These inner detectors will be surrounded by an electromagnetic calorimeter, or ECAL, which will consist of alternating layers of scintillating bars and Pb sheets. The purpose of the ECAL is to reconstruct any electromagnetic energy produced by events generated in the inner detectors (or, in the case of the P0D, any electromagnetic energy leaking out of the side from events near the edge of the detector). This will allow a measurement of the $\pi^0$s created in neutrino interactions, a critical input to determining the background these particles create in Super Kamiokande (and their effect on the CCQE/non-CCQE ratio), and also assist in determining the intrinsic $\nu_e$ contamination of the beam.

At most accelerator fixed-target experiments the particles of interest go primarily forward (i.e., continue in the beam direction). However, at the peak of the oscillation energy for T2K the muons produced in CCQE interactions are often found at large angles to the beam. Some of these muons penetrate all the way through the inner detectors and the ECAL and hit the magnet. In order to get a clean measurement of these events we have partially instrumented the magnet yokes with scintillator bars (which have slots built in for this purpose, as the magnet was used as the hadronic calorimeter by the UA1 experiment) to produce the Side Muon Range Detector, or SMRD.

Super Kamiokande

The Super-K detector has been successfully operated for atmospheric and solar neutrinos since 1996. In the energy range of interest the detector has a well-understood response to electrons, muons, and pions, and will be further studied and optimized as T2K continues. The detector has now been completely rebuilt following its 2001 accident (with modifications to prevent the accident from reoccurring) and is once again in operation. In the last year the performance of the detector has been substantially enhanced with new, dead-time free electronics and new DAQ software. The old electronics/DAQ only saved data when a trigger occurred (a set number of phototubes were hit within a given time), the new electronics will write every phototube hit for offline triggering and event building. Furthermore the new electronics are linear over a much larger range of phototube charges, allowing a better reconstruction of higher-energy events. The new electronics were installed (in only two weeks) in August/September 2008, and since September 6, 2008 Super Kamiokande has been running as SK IV. The new systems are
working extremely well and all calibrations have now been performed to prepare Super Kamiokande to take T2K data.

As mentioned earlier the high effective granularity of the Super Kamiokande detector allows the accurate measurement of the energy, position, and direction of charged particles in the few MeV–few GeV energy range, and the pattern of hit phototubes also allows electrons to be distinguished from heavier particles like muons or pions. For the T2K electron neutrino appearance measurement it is also critical to distinguish π⁰’s from electrons, which is possible because π⁰’s decay to two gammas that leave two rings in the detector. This fails if the decay is highly asymmetric and one of the gammas produces too few hits to be identified as a second ring; however, this happens rarely (and since the decay kinematics are known, the number of events with missed rings can be accurately estimated from the number of well-reconstructed events). Figure 7 illustrates this, showing the hit patterns from typical muon, electron, and π⁰ events. This event discrimination is good enough to remove all but a handful of background events from the electron neutrino appearance sample.

Sensitivity of T2K

There are two main issues for sensitivity of the appearance analysis. First, the number of events is small, and therefore everything must be done to increase the integrated beam power (and the efficiency of the analysis). Second, as the value sin²2θ₁₃ is reduced below the current limit, the background becomes a significant fraction of the total event rate so systematic uncertainties in estimating the background become significant. The disappearance measurement, on the other hand, is mostly about systematics—in particular, the energy scale and the shape and normalization of the non-CCQE background. Based on an analysis of simulated data from the T2K beam and estimates of the near detector performance, we believe that we will be able to achieve the following targets for systematic uncertainties:

- Uncertainty below 10% in the number of appearance backgrounds.
- νμ event rate normalization uncertainty less than 5%.
- Width of the νμ spectrum known to better than 10%.
- Linear distortion of the νμ spectrum known to better than 20%.
- Energy scale understood at the 2% level.
- CCQE/non-CCQE event ratio known to better than 5–10%.

Assuming these are achieved, and assuming a run equivalent to 8 × 10²¹ protons on target at the Main Ring beam energy of 30 GeV, which corresponds to five years of running (10⁷ seconds per year) at the nominal accelerator power of 750 kW, we expect the appearance sensitivity shown in Figure 8. The precision for the disappearance analysis depends on the actual values of the mass difference and mixing angle, but should approach a few percent for both parameters. The time it takes to reach this sensitivity will primarily depend on the power delivered from the accelerator; however, one year’s nominal running at 100 kW main ring power would already be enough to give T2K sensitivity to electron neutrino appearance beyond any existing experiment.

The Further Future

The longer-term plans for the J-PARC facility call for an increase in the beam power to 1.7 MW, and perhaps beyond, which (assuming that we can modify our target to survive a beam of that power) would at very least allow T2K to explore still smaller values of sin²2θ₁₃. If the value of sin²2θ₁₃ turns out to be favorable, that is, not too far below the current limit, it would even be possible to search for CP violation if we increase the beam power and build a new far detector. This has led to the proposal to build the Hyper Kamiokande experiment, which would consist of two 450 kton water Cerenkov detectors. A variant on this idea would be to place one of the two 450 kton modules at Kamioka, the other in South Korea where the T2K neutrino beam re-emerges from under the earth. Another possibility is to build a large volume liquid argon TPC, which has some advantages in event identification over a water Cerenkov. In addition to these there is also a proposal to build an additional set of near detectors 2 km from the beam target, where the near/far spectral corrections are very small and we could improve the systematic uncertainties in our measurements. Time will tell the best way to go forward, but it is certain that T2K will remain a flagship experiment for the world’s neutrino physics program for many years to come.

D. WARK
feature article

Japan Spallation Neutron Source (JSNS) of J-PARC

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Introduction

Development of accelerator-based neutron sources began after the 1970s, starting with electron accelerators using the bremsstrahlung photoneutron reaction. Now proton accelerators are the main drivers for neutron sources because of the efficiency of the spallation nuclear reaction for neutron yield (spallation source). Consequently, development of accelerator technology increases the power and neutron flux of spallation sources [1]. The pulsed nature of accelerator-based neutron sources in most cases can give large advantage in experiments using the time-of-flight (TOF) method. Moreover, because the heat dissipates slowly in the period between pulses the instantaneous power and neutron flux can be very high (thermal shock remains a problem to be overcome at the highest levels of proton power) [2]. Hence, building spallation neutron sources instead of reactors is becoming a world trend as demonstrated by the Spallation Neutron Source (SNS) in Oak Ridge, Tennessee (U.S.A.) and JSNS (what is called Japan Spallation Neutron Source) in the J-PARC, on which we describe here recent development. China has started construction of the China Spallation Neutron Source (CSNS), and quite recently a European Spallation Source (ESS) construction site has been decided on in Lund, Sweden after a tough bidding against Spain and Hungary.

High energy protons from an accelerator can instantaneously create large numbers of neutrons from heavy nuclei: 1 GeV proton produces about 25 neutrons from a heavy metal target such as lead, mercury, and so on with heat deposition in the target as low as only about half of the proton beam power—one order of magnitude lower than fission reactions for the same number of time averaged neutron fluxes. Spallation reactions occur above 100 MeV of proton energy and the neutron yield almost linearly increases with increasing the proton energy. In the case of the JSNS (proton power: 1 MW, proton energy: 3 GeV, proton current: 333 mA, proton pulse time width: 1 μs, frequency: 25 Hz), each proton pulse contains $8 \times 10^{13}$ protons, therefore $6 \times 10^{15}$ neutrons come out from target. This is $1.5 \times 10^{17}$ neutrons per second, whose time averaged intensity

![Figure 1](image1.jpg)

**Figure 1.** (a) Pulse Peak Intensity of CM, DM, PM in comparison with the cold source of ILL (Grenoble), (b) Pulse width of each moderator [3].
can be almost equivalent to that of a 15 MW research reactor. However, its peak intensity can be 500 times higher than the reactor counterpart. As described later, given a proper instrument, actual scattering experimental performance can be 500 times better than that with reactor source (cf. Figure 1).
MW Pulsed Spallation Neutron Source, JSNS

Overview of JSNS

Figure 2 shows an overview of JSNS. An 1-MW proton beam accelerated by the 3 GeV rapid cycle synchrotron (RCS) is injected to a mercury target located at the center of the target assembly. The mercury is circulated through a target vessel made of SS-316LN for heat removal. The injected protons induce spallation reactions with nuclei of mercury and produce neutrons.

The produced neutrons are mostly in a MeV energy region by evaporation process of excited nuclei. Energies of neutrons have to be decreased by nearly 10 orders of magnitude to have cold neutrons to be suitable for neutron scattering experiments. For this purpose, three distinct moderators in which supercritical hydrogen at 20 K and 1.5 MPaG flows are equipped as shown in Figure 3. Those moderators have been designed to be dedicated for (1) high intensity: a coupled moderator (CM) located under the mercury target, (2) good resolution: a decoupled moderator (DM), and (3) very high resolution: a poisoned decoupled moderator (PM). The latter two are located above the mercury target. The performances are shown in the Figure 1 (a) peak intensity and (b) pulse time width. Hydrogen moderator vessels for both the DM and PM except for neutron extraction windows are covered with a neutron absorber made of Ag-In-Cd (AIC) alloy to narrow the pulses, which can realize a cut off energy of 1 eV in a 1 MW neutron field. A Cd plate, which is called “poison,” is inserted in the moderator vessel of PM for further sharpening pulses.

The target and moderators are surrounded by a beryllium and steel reflector to enhance the intensity, and further by steel and concrete shields to attenuate high energy neutrons outside of a biological shield. After serious discussions with users, we decided to have 23 neutron beams ports, 11 ports view CM, 6 for DM, and 6 for PM. This decision was very unique among spallation facilities. Actually in the past a prejudice was dominated that only sharp moderator can be suitable for high resolution instruments, but it was turned over by introducing pulse shaping chopper or taking long flight path with supermirror guide.

Birth of Pulsed Neutrons in J-PARC

After a 7-year construction since 2001, off-beam commissioning of JSNS was completed to be ready for receiving proton beam at the target in May 2008. In order to catch the first pulsed neutrons, a current mode time-of-flight (C-TOF) detector system, a 4Li-glass scintillation detector coupled with a photomultiplier tube (PMT) [4], was arranged at a test beam port at the beam line No. 10 (BL10), NOBORU instrument [5]. Anode current signals from the PMT on neutron detection are recorded directly by an oscilloscope, which is very suitable to measure neutrons by a single shot of the proton beam.

After confirming proper proton beam transport from the 3 GeV RCS to JSNS, a neutron beam shutter of BL10 was opened and a 3 GeV proton beam containing $4 \times 10^{11}$ protons was introduced to the mercury target at 14:25 on May 30, 2008. Soon after that, a TOF spectrum appeared on a display of the oscilloscope as shown in Figure 4.
Finally, the first memorial neutron pulse by the spallation reaction at JSNS was confirmed successfully, that is, the birth of pulsed neutrons at J-PARC.

The World’s Highest Performance

After the birth of pulsed neutrons, efforts have been made to measure neutronics performance of JSNS and we could demonstrate two of the world’s highest performances through the measurements.

One is the world’s highest resolution as was demonstrated at the Super High Resolution Powder Diffractometer (SuperHRPD) [6] at BL08, which has a long flight path of 94.2 m and is viewing the PM. Figure 5 shows diffraction data from a silicon sample measured at SuperHRPD in comparison with those measured at the Sirius instrument that was a powder diffractometer at the KENS facility. It is obvious that the diffraction peak of SuperHRPD is much narrower than that of Sirius, and has negligible pulse tails. The excellent resolution makes it possible to resolve two adjacent diffraction peaks to give much detailed analyzing ability for crystal structure. Since the resolution of SuperHRPD, Δd/d = 0.0353% where d is a lattice spacing, was achieved at the back scattering position with He-3 detectors, which is a world record and can be improved to the design value, 0.030%, after fine adjustments and applying time focusing. So far the world’s record was 0.05% achieved at the ISIS facility in the United Kingdom.

Another world’s highest performance is high neutron flux intensity. We have measured neutron flux intensities for almost all available neutron instruments by the gold foil activation method. The highest intensity was confirmed at the exit of a neutron guide of an inelastic scattering instrument, 4D Space Access Neutron Spectrometer (4SEASONS) [7] at BL01 viewing CM. A neutron flux integrated below 0.4 eV is $1 \times 10^5$ n/s·cm² at 20 kW beam power. This is equivalent to $3 \times 10^9$ n/s·cm² at 1 MW beam power. This value can be the highest among currently existing spallation neutron sources in the world owing to the innovative design of CM, high reflectivity of the super-mirror guide, and the power of accelerators at J-PARC as well.

The high intensity cold neutron flux of JSNS is comparable to thermal fluxes in the reactor hall of Japan Research Reactor No. 3 (JRR-3) at JAEA, and is about 10 times higher than the cold neutron fluxes in the guide hall of JRR-3. In a history of spallation neutron source development, efforts have been devoted to increase neutron flux intensities to catch up with that of fission reactor sources. Although the peak neutron intensity of pulsed spallation sources has been already much higher than reactor sources, now we could confirm that spallation neutron sources could certainly catch up with reactor sources even in terms of time-averaged neutron flux intensity.

Physics Reproduced in Engineering

Neutronics Simulation code PHITS [10] has had a key importance for designing work of the J-PARC facilities. The code can treat high-energy nuclear physics up to TeV for various particles such as p, n, π, μ, K, e, γ, d, t, α, heavy ions, and so on. It can cover incoherent neutron scattering by molecules in meV and μeV regions as well. Engineering parameters needed for designing JSNS, such as neutron and

Figure 6. Comparison of measured and calculated absolute neutron spectral intensity (a) and pulse shapes (b).
photon fluxes, nuclear heating, radiation damage of materials, production of radioactive nuclei, dose rate, and background level in instruments have been obtained by simulation calculations with a detailed calculation model of JSNS.

To estimate how nicely the simulation calculations can predict nuclear parameters, absolute neutron spectral intensity and pulse shapes were measured at NOBORU, and compared with calculated data as shown in Figure 6. The calculation processes go through a huge number of scattering processes in a vast range of an energy scale in more than 13 orders of magnitude, and treat the neutron flux intensity in more than 10 orders of magnitude in the spacial dimension of about 10 m scale in the calculation model. Nevertheless, excellent agreements are seen between the measured and calculated data. Accordingly, it can be concluded that a variety of physical phenomena including high-energy nuclear physics can be reproduced accurately in engineering.

Uniqueness of Instrumentation

Neutron scattering can give atomic structural information and dynamic character of atoms in condensed matter. Because of the nature of the scattering process of neutrons and target nuclei, even light elements like hydrogen and lithium can be easily observable, hence, neutron scattering has been widely recognized to be a very important tool to study materials in microscopic scale in condensed matter science, ranging biology, chemistry, polymer science, solid state physics, material sciences, and even engineering-industrial research. Not only for the academic sector, we are making efforts to enlighten the industrial sector to use neutrons. At this moment we are constructing/planning the following instruments to cover demands from vast scientific disciplines [3] (cf. Figure 7):

1. powder diffractometers
2. single crystal diffractometers
3. small angle scattering instruments
4. reflectometers
5. inelastic scattering/spectroscopy instruments
6. neutron imaging instruments
7. prompt gamma detection instruments.

In a pulsed neutron source, we can naturally use the TOF method. Neutrons are counted as a function of flight time, starting at neutron emission at proton bombardment. Neutrons propagate along a flight path, are scattered by a sample, and detected by a detector at a certain scattering angle. Peak pulse width is maintained during the propagation from the source to the detector. Because of this, a sharp peak width from a decoupled moderator is preferable for a high resolution measurement with long flight path.

Figure 7. Perspective image of the experimental hall of JSNS.

Figure 8. TOF (time of flight)—Distance diagram. Neutrons having certain energy propagate along a line from the source to the sample, scattered by the sample, and observed at detectors. Multi opening chopper lets neutrons go through if their speed (energy) matches with the opening times of chopper.
separating peaks at the detector. But this was an old concept of instruments in pulsed neutron source in the past. Instead, JSNS has taken much advanced concepts for instrumentation by taking a pulse shaping chopper system, which cut out high peak flux and sharpen the peak from CM and a new concept of multi-repetition multiplicity method (RRM), in which multi-incident energy can be utilized at the same time in one time frame. Those concepts largely stepped up performances of instruments. In Figure 8 the concept of RRM is described [8].

In the conventional neutron scattering spectroscopy only the neutron beam with a single incident energy has been used, where there exists an unused time window between neutron pulses. However, instead of the single-opening chopper, if we use a multi-opening chopper as shown in Figure 8, multi-incident energy can be utilized and observed scattering occurring for each energy can be detected at detectors.

RRM was applied to measure a scattering function of a quasi–one dimensional antiferromagnet CuGeO₃ [9]. This material contains “hierarchical spin dynamics.” At low temperature a spin-Peierls transition occurs and spin singlet states appear with a spin gap and in the excited states the magnetic spectrum exhibit a typical feature of one-dimensional antiferromagnet, a spin wave excitation, and a continuum excitation at higher energy region. In such a case, by using RRM one can simultaneously obtain the inelastic scattering signals at each part of the hierarchical spin dynamics as shown in Figure 9. The observation was successful by not only the cutting-edge hardware components but more importantly, event-recording data acquisition system. The result has given a very strong impact to communities with giving a prospective view in science to be done by neutron in the near future.

Concluding Remarks

We have confirmed JSNS has expected achievements in the target and instrument performances. Although accelerator power is still kept at low power due to unexpected issues found in the accelerator component, the results obtained through commissioning promise us an excellent platform to perform neutron scattering sciences in the near future after recovery of the power.

Acknowledgments

The authors appreciate their colleagues at the Materials Life Science Division of J-PARC Center. Their support and cooperation have been indispensable for the construction and commissioning of the facility.

References


Figure 9. Four colored figures show the data taken from four different incident energies of neutron beam between 12.6 meV to 150.7 meV.
The muon science facility (MUSE), along with the neutron, hadron, and neutrino facilities, is one of the experimental areas of the J-PARC project, which was approved for construction in a period from 2001 to 2008. The MUSE facility is located in the Materials and Life Science Facility (MLF), which is a building integrated to include both neutron and muon science programs. Construction of the MLF building was started in the beginning of 2004, and was completed at the end of the 2006 fiscal year. Then, we completed the installation of the primary 3 GeV proton beam-line (the so-called M2 tunnel) components in the beginning of 2007.

The 3 GeV proton beam from the RCS ring is transported through the beam transport line over a distance of about 300 m and focused onto the muon target in the M2 tunnel with a spot size that is as small as possible. We installed one graphite target with a thickness of 20 mm, and 24 mm in diameter, from which four secondary beam-lines are designed to be extracted leading into the experimental halls. Figure 1 shows a schematic drawing of the J-PARC Muon Facility, MUSE [1].

For Phase 1, we managed to install one super-conducting decay/surface muon channel with a modest-acceptance (about 40 msr) pion injector. On September 26, 2008, we finally succeeded in delivering the surface muon beam to the D1 muon experimental area. In front of a live audience, we demonstrated a μSR asymmetry measurement under a weak transverse magnetic field adopting an aluminum plate as a sample, using the 128×2 channels DAI-Omega μSR spectrometer. Figure 2 shows the first μSR asymmetry spectrum of the Al sample. Afterward, together with the audience, we celebrated the extraction of the first muon beam. Figure 3 shows a picture celebrating the first muon beam production at J-PARC MUSE. By undergoing the beam tuning, we are able to extract, at present, surface muons (μ+) rate of 8×10⁶/s and decay muons (μ⁺/μ⁻) rate of 10⁶/s at 40 MeV/c and up to 10⁷/s at 90 MeV/c with a beam size of 50 mm in diameter, which are calibrated intensity with 1 MW proton beam intensity, although the present average intensity is as much as 20 kW. These intensities, at 1 MW operation, correspond to more than seven times those at the RIKEN/RAL Muon facility [2].

In addition to Phase 1, we are planning to install one surface muon dedicated channel with a modest-acceptance (about 50 msr) and one super omega muon channel with a large acceptance of 400 msr for the study of thin film magnetism utilizing ultra slow μ⁺.

**Muon Sciences**

Muons can be used in various fields of scientific research, including: (1) use of the muon as a spin probe
sensitive to the microscopic magnetic properties of various new materials; (2) non-destructive element analysis to be applied to not only industrial use, but also bio-medical studies, and so on; (3) muon catalyzed fusion and its application to energy resource problems; and (4) investigation of the electromagnetic properties of a nucleus such as charge distribution and nuclear polarization; and (5) fundamental muon physics such as precise measurements of particle properties of muons, hunting for rare decays, and so on.

**Muon Spin Probe for Condensed Matter Studies**

A muon injected into matter acts as a very sensitive probe of microscopic magnetic fields in various materials. Spin polarization of 100% for both surface $\mu^+$ and backward $\mu^+/\mu^-$ and 50% polarization for keV ultra-slow $\mu^+$ can be obtained. By observing the time evolution of the anisotropy of the $e^+/e^-$ emitted from the muon decay the local magnetic field and its fluctuation can be studied. This is known as the $\mu$SR method. The characteristic time scale for $\mu$SR, detecting paramagnetic spin fluctuations of a 1 $\mu_B$ moment, is $10^{-9} \sim 10^{-5}$ s, between the sensitivity time ranges of neutron scattering ($10^{-4}$ s). Moreover, the true microscopic nature of muon probe allows us to study spatially inhomogeneous magnetic systems where neutron diffraction is hardly observed. Because of these unique features, the $\mu$SR method has been applied in a variety of research fields where the spin dynamics and/or local magnetic structure plays an important role such as magnetism and high-$T_c$ superconductivity. Takeshita et al. already published a paper demonstrating the presence of a macroscopic phase separation between the superconducting and magnetic phases in Co-Doped Iron Pnictide CaFe$_{1-x}$Co$_x$AsF, utilizing the MUSE facility [3].

Another important aspect is that the muon simulates the electronic structure and dynamics of hydrogen (H) atom in matter. In particular, paramagnetic Mu center has been serving as a unique tool to study the isolated hydrogen isotopes in elemental and compound semiconductors. It is now well established that residual hydrogen plays a crucial role in determining the bulk electronic properties of these materials. Since little or no information has been available from hydrogen electron paramagnetic resonance, Mu will remain as an complementary source of information on isolated H [4].

**Ultra-Slow $\mu^+$ Source and Its Application**

Combining the advantageous features of the high intensity ultra-slow muon beam at the J-PARC MUSE (which is assigned to be Phase 2 project) and the short range nature of ultra-slow muons, new experiments of various kinds will be realized. Ultra-slow muons can be stopped at/near the surface and, moreover, can be easily accelerated up to any voltage as a result of their small emittance. Therefore, thin film materials grown by molecular beam epitaxy (MBE) or ion implantation can easily be investigated in situ, eventually contributing to the realization of new multi-functional materials. Also, the high intensity ultra-slow muon beam enables us to simulate hydrogen reaction dynamics on surfaces, such as catalytic reactions on metal surfaces [5].

Ultra-slow $\mu^+$ is also important for fundamental and particle/nuclear physics. An intense thermal Mu converted from intense keV $\mu^+$ will be used for precise QED testing in the precise measurement of the Mu 1s-2s transition, or g-2 experiment, and so on. Furthermore, it is also applicable to the search for Mu–anti-Mu conversion.

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**Figure 2.** The first $\mu$SR asymmetry spectrum of the aluminum target.

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**Figure 3.** A picture celebrating the first muon beam production at J-PARC MUSE.


**Sciences using Negative Muons**

A negative muon behaves like a “heavy electron” in matter. The full range of possible applications of muonic atom science can be realized only with a high intensity negative $\mu^-$ beam, since $\mu^-$ obtained at the MUSE is originated from the 3 GeV proton having a large $\pi^-$ cross-section. Non-destructive analysis is one such example. Components present in samples in only very tiny amounts can easily be quantitatively measured by observing the characteristic X-rays from muonic atoms. Its feasibility was already checked at J-PARC MUSE for the application to nondestructive analysis studies on Au and Ag concentration in the Japanese old coin, Tempo-Koban (a property of Prof. T. Saito, National Museum of Japanese History).

The electromagnetic properties of a nucleus such as charge distribution and nuclear polarization have been studied intensively by using muonic atoms. We have, however, little knowledge on the charge radii of short-lived nuclei. A new field of physics will be explored for the first time at J-PARC, by combining the high intensity negative muon beam with an unstable nuclear beam [6].

**Muon Catalyzed Fusion**

When a negative muon stops in a mixture of deuterium and tritium, it attains a deuterium nucleus ($d$) and a tritium nucleus ($t$) to form a muonic molecule ($dt\mu$) in which the muon holds the $d$ and $t$ nuclei together. Since the muon is 207 times heavier than an electron, the muonic molecule is much smaller than an ordinary DT molecule. Thus, the fusion reaction can occur again and again. Each muon can spontaneously induce a number of fusion reactions and hence serves as a catalyst for the nuclear fusion process. Although the lifetime of the muon is only 2.2 $\mu$sec, more than 100 fusion reactions are catalyzed per muon. A pulsed muon beam has two main advantages for fusion studies. One is that tiny signals can be extracted from the huge background noise due to tritium decay. For example, muonic helium X-rays due to $\alpha$– sticking can be detected even for a D-T mixture with high density and high tritium concentration. This method was first realized at KEK-MSL and research in this field has been expanded in the experiment at RIKEN-RAL [7]. The other feature is that extreme target conditions can be realized by synchronizing an external stimulus with the beam pulse. The much higher beam intensity available at the Muon Science facility of the J-PARC makes feasible and provides a great opportunity for challenging experiments that may eventually lead us to find suitable conditions to overcome break-even for energy production.

**Summary**

By taking advantage of the world’s strongest pulsed $\mu^+$/$\mu^-$ beam at J-APRC MUSE, we may be able to experiment on tiny volumes like small crystals or gaseous samples, or observe dynamics every minute by shortening the measuring duration. But it is very important to emphasize that all the scientific research subjects will be done utilizing unique and excellent features of the pulsed muon beam, which are:

1. Long time-range measurements can be realized for muon-associated events, such as muon decay or $\mu^+$ SR, in a rate-unlimited manner;
2. Easily coupled with extreme experimental conditions, which are effectively realized only in pulsed mode (which enables us to do muon spin RF resonance, muon state laser resonance, etc.);
3. Phase-sensitive detection of weak muon-associated signals can be achieved under a large white-noise background such as $\mu$CF experiment under a large tritium Bremsstrahlung background. Of course, pulsed muon is complementary to the DC muon.

**References**

Fundamental Science for Neutrons

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A pulsed cold neutron beam-line “Neutron Optics and Physics (NOP)” for the study of neutron optics and fundamental physics is being constructed at the beam port BL05 of the Materials and Life Science Facility of the J-PARC [1].

A three-fold multi-channel supermirror guide (Figure 1) is installed in the upstream section of the NOP beamline to provide cold neutrons to three beam branches: the Low-divergence-beam Branch, the Unpolarized-beam Branch, and the Polarized-beam Branch as shown in Figure 2. The designed performance of each beam branch is summarized in Table 1. High energy neutrons are absorbed in the shield blocks in the upstream section. After the NOP beamline accepted neutrons on December 9, 2008, the commissioning of the beam-line is in progress.

Currently, the apparatus for the lifetime measurement of the in-flight neutron β-decay is being prepared at the Polarized-beam Branch. The polarized neutrons would be sharply bunched using a spin flip chopper to define the fiducial volume and to suppress the background γ-rays. We expect the improvement of the accuracy of in-flight neutron lifetime using the instantaneously luminous pulsed cold neutrons from the J-PARC to clarify the large deviation of the values of the lifetime obtained in various methods. The decay measurement will be extended to the measurement of spin-angular correlation terms for the improvement of the unitarity of the CKM matrix.

The installation of a multilayer neutron interferometer is scheduled in November of 2009. The multilayer interferometer will be used to improve the sensitivity to the neutron phase difference induced by the geogravity and the Aharonov-Casher effect by using the capability to observe the interference in a wide wavelength region, the
freedom to enlarge its size and the suppressed dynamical diffraction effect. A challenge to enlarge the interferometer size to observe the general relativistic phase difference is also planned.

An accurate measurement of the angular distribution of the scattering cross-section by noble gas is scheduled at the Unpolarized-beam Branch for the inclusive search for medium-range forces.

The apparatus design for the measurement of the neutron electric dipole moment in the crystal diffraction and the expansion of wavelength region into very-cold and ultracold regions is in progress together with the development of advanced neutron optics.

Reference

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**Table 1.** Design values of the beam characteristics of beam branches of J-PARC MLF BL05 (NOP beamline).

<table>
<thead>
<tr>
<th>Branch</th>
<th>Beam intensity</th>
<th>Beam size</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-divergence</td>
<td>$9.2 \times 10^5$ cm$^{-2}$ µsr$^{-1}$ s$^{-1}$ MW$^{-1}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Unpolarized</td>
<td>$1.2 \times 10^9$ cm$^{-2}$ s$^{-1}$ MW$^{-1}$</td>
<td>5 cm × 4 cm</td>
<td>—</td>
</tr>
<tr>
<td>Polarized</td>
<td>$4.0 \times 10^9$ cm$^{-2}$ s$^{-1}$ MW$^{-1}$</td>
<td>10 cm × 4 cm</td>
<td>0.998 ($E_n &gt; 1.5$ meV) (average 0.98)</td>
</tr>
</tbody>
</table>
Nuclear Transmutation as a Phase 2 Project

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Introduction

One of important issues for sustainable utilization of nuclear energy is the management of high-level radioactive wastes (HLW). To reduce the burden for disposal of HLW, the Japan Atomic Energy Agency (JAEA) has been conducting research and development (R&D) on nuclear transmutation technology for long-lived nuclides such as minor actinides (MA) and long-lived fission products (LLFP). Two candidate systems are being explored for the nuclear transmutation: an accelerator-driven subcritical system (ADS) and a critical fast breeder reactor (FBR). The ADS has remarkable advantages for effective transmutation of MA in comparison with critical reactors from viewpoints of safety margin and flexibility to accept various fuel compositions [1].

The ADS proposed by JAEA is an 800 MW (thermal power), nitride fueled, Pb-Bi eutectic (LBE) cooled fast subcritical reactor driven by a spallation neutron source consisting of an LBE target and a 1.5 GeV, 20–30 MW proton accelerator as shown in Figure 1 [2]. This ADS can transmute 250 kg of MA every year, which corresponds to those produced in 10 units of light water reactors of 1 GW (electric power). To realize such a large-scale ADS, some technical issues should be overcome. The issues are, for example, reliability of the accelerator, beam transport system, high power spallation target technology, integrity of beam window, reactor physics and controllability of subcritical system, and handling of MA fuel.

For the experimental R&D for most of the aforementioned technical issues, JAEA plans to build the Transmutation Experimental Facility (TEF) as a Phase-2 project of J-PARC [3,4].

Outline of Transmutation Experimental Facility (TEF)

The TEF consists of two buildings: the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T), as shown in Figure 2.

TEF-P is a zero-power critical facility that can be operated with a low-power proton beam to investigate the reactor physics and the controllability of ADS. TEF-T is a

Figure 1. Concept of commercialized ADS for MA transmutation in the future.

Figure 2. Concept of Transmutation Experimental Facility (TEF).
material irradiation facility that can accept a proton beam of 200 kW-600 MeV into a spallation target of LBE.

Transmutation Physics Experimental Facility (TEF-P)

The first purpose of TEF-P is to research the reactor physics aspects of the subcritical core driven by a spallation source using 600 MeV proton beam, which will be the first experiment in the world. The second purpose is to demonstrate the controllability of the subcritical core. The third purpose is to research the transmutation performance of both the subcritical and the critical systems using a certain amount of MA and LLFP with installing proper shielding, cooling, and handling devices.

For the aforementioned purposes, the high thermal power is not necessary; a power level of critical experiments such as 100 W is preferable from a viewpoint of the accessibility to the reactor core.

The TEF-P is therefore designed with referring to the existing fast critical assembly (FCA) in JAEA. Figure 3 shows a conceptual view of the assembly. The fuel is loaded in the fixed and the movable half assemblies. The movable assembly approaches to the fixed one, and they contact each other for the operation.

Low current proton beam (about 10 W) is extracted by using a laser charge exchange technique from high-intensity beam-line of 200 kW (0.33 mA, 600 MeV) most beam of which is introduced into TEF-T. The 10 W proton beam corresponds to the source strength of $1.5 \times 10^{12}$ neutrons/s, which is strong enough to measure the power distribution even at a deep subcritical state.

Using TEF-P, various experimental studies can be conducted. As for the neutronics in the subcritical system, power distributions, effective multiplication factors, effective neutron source strengths, and neutron spectra will be measured by changing the subcriticality and the spallation source position parametrically. The material of the target will also be altered with Pb, Pb-Bi, W, and so on. It is desirable that the core has an ability to reach the critical state in order to ensure the quality of experimental data of the subcriticality measurement.

As for the demonstration of the hybrid system, feedback control of the reactor power will be tried by adjusting the beam intensity. Operating procedures at the beam trip and the re-start are also to be examined.

As for the transmutation characteristics of MA and LLFP, fission chambers and activation foils will be used to measure the transmutation rates. The cross-section data of MA and LLFP will be also measured by the time-of-flight (TOF) technique with the short-pulsed proton beam. Partial mock-up of the transmutation systems, both ADS and FBR, with installing MA fuel is the ultimate target of TEF-P, where air cooling and remote handling devices for MA fuel

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Figure 3. Concept of Transmutation Physics Experimental Facility (TEF-P).

Figure 4. Two types of spallation target of ADS Target Test Facility (TEF-T).
should be equipped. Figure 3 (bottom) shows a schematic view of the partial loading of pin-type MA fuel around the spallation target.

**ADS Target Test Facility (TEF-T)**

The beam window of ADS plays an important role as a boundary between the accelerator and the subcritical core. It is, however, situated in the severe circumstance: heavy irradiation by both protons and neutrons, thermal stress by proton beam transients, mechanical stress by the pressure difference between the counter flow of the liquid metal target and the vacuum in the beam duct, and corrosion/erosion by LBE. The feasibility of the beam window, therefore, should be demonstrated at a top priority in the ADS development.

TEF-T is a proton-neutron irradiation facility dedicated to the ADS. TEF-T can accept a 600 MeV, 200 kW proton beam to an LBE target. To demonstrate the feasibility of the beam window, the proton beam density at the beam window should coincide with that of the future ADS plant. In the design of the ADS plant, a 30 MW proton beam of 1.5 GeV (20 mA) is assumed to be available, where the diameter of the beam is defocused to about 45 cm. This means proton beam density is about 13 μA/cm² in average. At TEF-T, on the other hand, the proton beam of 0.33 mA will be focused to 40 mm in diameter, which results in the beam density of about 26 μA/cm² in average; this beam density is considered to be high enough for the experimental demonstration.

The neutron flux exceeds $10^{14}$ n/cm²/s at the center of the target and $10^{13}$ n/cm²/s at the peripheral region of 300 mm in diameter and 300 mm in length, where various materials can be irradiated by fast neutrons.

Two kinds of target vessel are being considered: one is a “demonstration-type” and the other is an “irradiation-type” as shown in Figure 4. The demonstration-type simulates the shape of the beam window of the ADS, where the LBE heated by the proton beam flows toward the beam window. On the other hand, the irradiation-type is designed to optimize the irradiation conditions for samples. The direction of the LBE flow will be opposite in comparison with the demonstration-type.

The mechanical properties of irradiated structural materials of the target vessel, as well as the irradiated samples, will be tested. In addition to these tests, the effects of the corrosion and erosion by LBE and the spallation products will be studied precisely by changing the parameters such as the temperature, the irradiation period, the flow speed, and the oxygen concentration in LBE. Plenty of experiences for the operation and the handling of the high power spallation target can be accumulated at TEF-T.

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2010
January 15
Budapest, Hungary. Second session of the “NuPNET Governing Council” – GC2
http://www.nupnet-eu.org/wps/portal/upcoming-events.html

January 25–28
Caen, France. Spiral2 Week
http://spiral2ws.ganil.fr/2010/week/

January 25–29
Bormio, Italy. XLVIII Winter Meeting on Nuclear Physics, in memoriam of Ileana Iori
http://panda.physik.uni-giessen.de:8080/indico/conferenceDisplay.py?confId=16

March 1–4
Niigata, Japan. Forefronts of Researches in Exotic Nuclear Structures
http://niigata2010.cc.niigata-u.ac.jp/

April 12–16
Saariselkä, Finland. International Conference on Trapped Charged Particles and Fundamental Physics (TCP2010)

May 31–June 3
Madrid, Spain. NuPECC LRP Town Meeting
http://www.nupecc.org/index.php?display=misc/meetings

May 21–25
Vetri sul Mare, Italy. 10th International Spring Seminar on Nuclear Physics
http://vietri2010.na.infn.it

June 6–11
Lamoura, France. EURORIB 2010
http://indico.cern.ch/conferenceDisplay.py?confId=61310

June 7–12
Kyiv, Ukraine. Current Problems in Nuclear Physics and Atomic Energy
http://www.kinr.kiev.ua/NPAE-Kyiv2010/

July 2–7
Torino, Italy. Euroscience Open Forum ESOF2010
http://www.esof2010.org/

July 4–9
Vancouver, Canada. INPC 2010
http://inpc2010.triumf.ca/

July 19–23
Heidelberg, Germany. Nuclei in the Cosmos NIC XI
http://www.sw.uni-heidelberg.de/nic201

August 9–13
Fort Worth, Texas, USA. International Conference on the Application of Accelerators in Research and Industry CAARI 2010
http://caari.com/

August 30–September 5
Zakopane, Poland. Zakopane Conference on Nuclear Physics
http://zakopane2010.ifj.edu.pl/

September 13–17
Athens, Greece. 10th European Conference on Accelerators in Applied Research and Technology (ECAART10)
http://www.ecaart10.gr

September 27–October 2
Juelich, Germany. The 19th International Spin Physics Symposium (SPIN2010)
http://www.fz-juelich.de/ikp/spin2010

2011
May 2–6
Saint Malo, France. FUSION11
http://fusion11.ganil.fr/

May 31–June 3
Leuven, Belgium. Advances in Radioactive Isotope Science (ARIS - 2011)
http://iks32.fys.kuleuven.be/aris/

More information available in the Calendar of Events on the NuPECC website: http://www.nupecc.org/