NEUTRINO AND OTHER BEAM-LINES AT J-PARC

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Abstract

To carry out T2K, a next-generation long base-line neutrino oscillation experiment connecting 295 *km* from Tokai to Kamioka, is one of the main motivations to construct J-PARC. It employs 50GeV proton synchrotron as a neutrino super-beam source, and Super-Kamiokande as a far neutrino detector. It can explore mass and mixing of neutrinos with unprecedented precision. It especially aims to observe tiny ν_μ-to-ν_e appearance signal for the first time. A neutrino beam-line is under construction at Tokai campus, and beam commissioning is scheduled in April, 2009. In this talk I present characteristic features of the beam-line and apparatus therein. I also introduce beam-lines at the other facilities in J-PARC.

PHYSICS MOTIVATION

Recently, the rapid progress in neutrino oscillation experiments has uncovered finite, but tiny, neutrino mass and mixing between its flavours. After the announcement by Mini-Boone[1], three neutrino flavour model has mostly been established. The Maki-Nakagawa-Sakata (MNS) matrix, mixing matrix between neutrino flavour eigenstates and mass eigenstates[2], has six observables through neutrino oscillation experiments: Two mass squared differences (Δm^2_{12}, Δm^2_{23}), three mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP phase (δ_{CP}). Through the past and present experiments in ten years, order of magnitude different Δm^2_{12} and Δm^2_{23} have been obtained (sign of Δm^2_{23} is yet unknown) and mixings between successive two eigenstates (1-2 and 2-3) are found to be nearly maximum [3,4,5]. While a mixing between 1st and 3rd eigenstates is known to be small, and only upper limit for $\sin^2 2\theta_{13}$ is obtained so far by reactor experiments [6].

We can investigate this 1-3 mixing by studying ν_μ-to-ν_e appearance through accelerator long-baseline experiments. K2K, the long base-line experiment between KEK PS and Super-Kamiokande running through 1999 to 2004, corrected about one hundred of accelerator-made neutrino events flying 250*km* away [7]. By using μ/e identification of the SK detector and applying tighter cuts to reduce electron-like background, one ν_e-like event was obtained [8]. It should be compared to the background, estimated to be 1.7. They are mostly coming from intrinsic beam ν_e, and also π^0 produced by neutral current inelastic interactions. It was a result with poor statistics, and also reduction of these backgrounds was necessary.

The T2K experiment, connecting 295 *km* from Tokai to Kamioka, is the first super-beam neutrino oscillation experiment, using J-PARC 50GeV main ring (MR) as a neutrino super-beam source [9] and Super-Kamiokande as a far neutrino detector. The design value of the proton beam power of the MR (750kW) is one hundred times larger than that of KEK-PS.

Figure 1: Layout of the T2K experiment

We are now constructing neutrino secondary beam-line and developing the apparatus therein towards completion in March 2009. The beam-line has many design improvements to study tiny ν_e appearance mode, which will be presented later.

J-PARC ACCELERATORS, FACILITIES AND BEAM-LINES

J-PARC, Japan Proton Accelerator Research Complex, is a joint facility of High Energy Accelerator Research Organization (KEK) and Japan Atomic Energy Agency (JAEA). It consists of high intensity proton accelerators to produce Mega Watt class primary proton beams, and surrounding experimental facilities [10]. Through the proton and fixed target interactions, variety of secondary particles (neutrons, pions, kaons, hyperons, antiprotons) and daughter particles (muons and neutrinos) are to be produced. These high-intensity secondary beams provide unique opportunities to explore frontiers together in particle and nuclear physics, in material and life science, and in nuclear transmutation technology.

J-PARC Accelerator Cascade

J-PARC accelerator complex consists of followings:

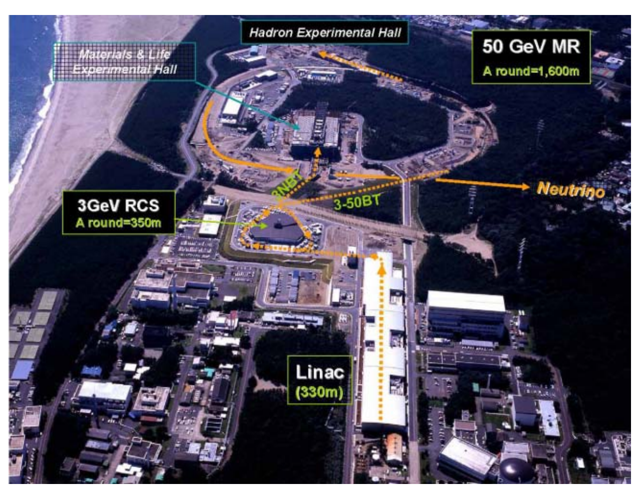

Figure 2: Bird-eye view of J-PARC.

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- 400MeV normal-conducting Linac. It is an injection system to the accelerator complex. After future upgrade to 600MeV by adding another super-conducting system, it will supply proton beam to Transmutation Experimental Facility (TEF) [11].
- 3GeV Rapid Cycling Synchrotron (RCS), which provides proton beams at 333μA (1MW) to the Material and Life science Facility (MLF). It will also play a role as a booster synchrotron of MR.
- 50GeV MR, which provides proton beams at 15μA (0.75MW) to nuclear and particle physics facilities at the Hadron Hall, and also to a neutrino beam-line.

Construction was started on April 2001, and most of the public works are now being completed. Installation of the apparatus has mostly been finished for Linac and RCS. Commissioning has already been started for Linac from November 2006, and acceleration to the day-one energy, 181MeV, has been achieved successfully on last January without notable beam loss [12]. For RCS, off-beam commissioning has been started in last April and beam run is scheduled in September 2007. For MR, installation is going on. Initial beam commissioning to establish closed orbit is scheduled in early FY 2008. After that, fast/slow extraction devices are going to be installed [13].

Materials and Life Science Facility (MLF)

Materials and life science experimental facility (MLF) has a muon source [14] and a spallation neutron source [15]. The facility is located at the interior of MR. Pulsed proton beam from RCS, with a current of 333μA and a repetition rate of 25Hz, is passed through a beam transportation facility called 3NBT to MLF (It goes over MR and the decay volume of the neutrino beam-line). After penetrating through a carbon target for muon production, the proton beam is incident on a liquid mercury target for neutron production. 4 muon beam lines and 23 neutron beam lines are going to be constructed. The intensity of muon and neutron flux is the world highest, and wide variety of researches in material science and life science would be promoted.

At the end of last April, construction of the experimental hall was all completed. Various components, devices, equipments are now being manufactured and installed, towards the completion scheduled within FY2007. The first beam to the MLF is expected in early FY2008.

The Hadron Hall

The Hadron Hall is an experimental site of the Nuclear and Particle Physics Facility, together with the neutrino beam-line. Main purpose of the facility is to realize a kaon factory, to promote the hyper-nuclear spectroscopy, studies for the strangeness degree in nuclear matter, kaon rare decay search, hadron spectroscopy *etc*. Various short-lived hadrons, including kaons and pions, will be produced from the interaction between fixed targets and the slowly-extracted proton beam. In July 2007, civil construction of the hadron hall will be completed. The operation of the hall is scheduled in the end of 2008.

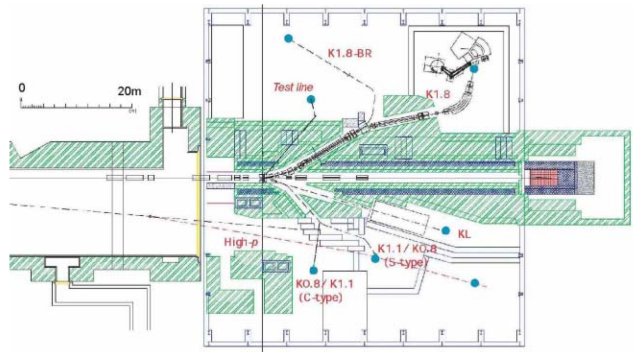

Figure 3: Layout of the Hadron Hall.

Fig.3 shows the beam-line layout. Through a matching section, the proton beam is shaped and bent to a switch yard section. At day-one, the facility will have single primary beam-line and a target (T1), while adequate capabilities are kept to install more primary beam-lines in the switch yard for future extension.

T1 target is a system composed of 5 Nickel disks of 360mm-ϕ and 54mm total width, which are partly soaked in cooling water. They are rotated by one cycle per a beam flat top to disperse heat over circumference. The beam loss due to the interaction on the target is about 30% of beam intensity, and about 200kW of heat will be released to the downstream components. Beam windows made of Beryllium will be installed to the both sides of T1 with pillow seals. At downstream of T1, a large vacuum chamber, central box, will be settled, where a copper collimator and radiation-hard magnets will be enclosed. The primary protons, which go straight through T1, are collimated and lead to a beam dump. It is made of 180 tons of thick copper plates with tapered hole at beam centre, and 90tons of iron plates.

There are three kaon beam-lines lead out from T1: K1.8 / K1.8-BR (left to the target), K1.1 / 0.8 (right), and KL (centre). At day-one, K1.8 has priority to be in operation for Ξ (S=-2) hyper-nuclear spectroscopy with the Super-conducting Kaon Spectrometer (SKS) [16]. Maximum of the central momentum is optimized to 2 GeV/c, since the Ξ production with (K^-, K^+) interaction has its maximum at 1.8 GeV/c. At the front end section, the line is extracted at 6 degree with respect to the primary beam-line. There are 1st and 2nd separation sections, which are composed of two 6m-long Electro-Static Separators (ESS), three vertical slits, and higher order correction magnets (A branch line, K1.8BR, will be constructed after the 1st separation section). For the Ξ hypernuclear spectroscopy, energy resolution of a few MeV is necessary. There is a beam analyzer section with a 4m-long D magnet with focusing Q magnets and tracking devices. By assuming day-one operation of 30GeV-9μA(270kW), the K^- single rate is expected to be more than 8×10^6 *ppp* before the beam analyzer section, and intensity of the negative kaon with 1.8GeV/c is 1.4×10^6 *ppp* at the final focus (for 750kW, it will be a factor 5 larger). K^-/π^- ratio is expected to be 7. The intensity corresponds to about 100 Ξ hypernucleus event per a month of data taking, which is enough to determine potential depth and energy levels with a few 100 keV of resolution. Λ hyper-nuclear gamma-ray spectroscopy by using large Ge detector array (Hyperball-J) and SKS will also be taken place [17]. The beam-line is tuned for 1.5GeV/c to enhance (K^-, π^-) reaction, where intensity is expected to be 0.54 $\times 10^6$ *ppp* at the final focus.

In the other side of K1.8, K1.1 (and branch K0.8), will be constructed. The beam intensity for the 1.1GeV/c negative kaon is expected to be 1.2×10^6 *ppp* for 50GeV-15μA operation, which is stronger than that of K1.8.

The KL is the line to study rare decay of neutral kaon, especially aims to measure branching ratio of $K_L \rightarrow \pi^0 \nu\nu$ [18]. It is sensitive probe to a direct CP violation in the quark sector. So far a KEK-PS experiment has the best upper limit, 2.1×10^{-7} at 90%C.L.[19], which should be compared to the Standard Model prediction, 2.8×10^{-11}. Forthcoming experiments aim to improve this to 10^{-13}.

THE NEUTRINO BEAM-LINE

The layout of the neutrino beam-line is illustrated in Fig.4. It consists of a primary beam-line, a target station (TS), a decay volume (DV), a beam dump (BD), muon monitors, and near neutrino detectors 280m downstream from the target. Unique feature of the beam-line is that, this is the first application of the off-axis (OA) beam configuration [20], where the centre of the neutrino beam direction is shifted by a few degrees towards underground with respect to the far detector. By adjusting the off-axis angle from 2 to 2.5 degree, we can tune the peak of the semi-monochromatic beam to the expected oscillation maximum (E_ν=0.8~0.65GeV). It is to be noted that quasi-elastic interactions are dominant under 1GeV energy, which is quite suitable to minimize the electron-like shower background caused by π^0, which are produced through neutral current inelastic interactions. The shorter length of the DV (100*m*) than that of K2K (200*m*) also reduces beam-intrinsic ν_e contamination coming from muon and K_{e3} decays. The ν_e contamination is estimated to be 0.4% for OA2.5, factor 5 lower than that of K2K.

Primary Beam-Line

The primary beam-line is to transfer fast-extracted proton beam from MR, with spill width of 4.2μs in every 3.64sec, to the production target. It consists of three sections: A preparation section, an arc section, and a final focusing section. The preparation section is composed of 12 normal conducting magnets and collimators, which accommodate 60π mm·mrad beam emittance. In the arc section with radius of 104*m* and the length of about 150*m*, the beam is bent about 80 degree by 28 Super-conducting Combined Function Magnets (SCFM) [21]. This is the first attempt to develop combined function magnet as superconducting device. It is 3.3*m* long, where dipole and quadrupole components are 2.6*T* and 18.6*T/m*, respectively. The applied current will be 7,345A for the 50GeV operation. Two SCFM magnets are assembled

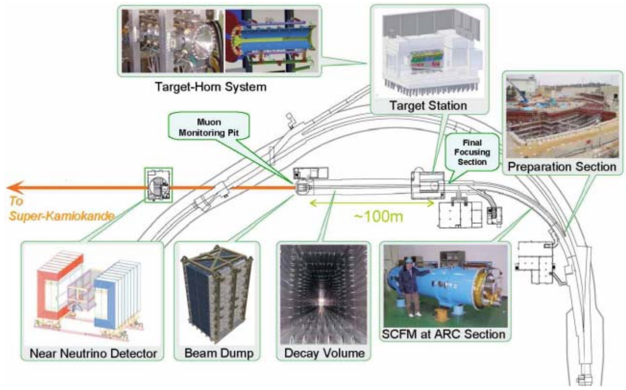

Figure 4: Schematic view of the neutrino beam-line.

inside of one cryostat (doublet). The final focusing section is composed of 10 normal conducting magnets.

Intensity (current transformer), position (electro-static monitor), profile (segmented secondary emission monitor), and beam-loss monitors will be installed.

Target Station, Target and Horn System

The target station is a building with a remote-handling crane, to maintain highly-irradiated horns and target from a distance. Main component is a large vacuum vessel made of 100*mm*-thick iron plates, where a production target, magnetic horn system, decay volume collimators, and related apparatus are installed and kept under helium atmosphere. Surface of the 100*mm*-thick iron plates are covered with water paths (plate coil) to cool down heat released from the target. Ceiling of the vessel is a large flange, which is closed and sealed with 120*mm*-thick aluminium plate. The helium vessel is enclosed in thousands tons of iron cast blocks and concrete shield blocks for radiation protection.

At the upstream of TS vessel, a beam window separates the helium atmosphere and the vacuum of the primary beam duct. It is made of two layers of Ti-alloy, where the compressed helium gas flows between them. The window has pillow seals on both sides for remote handling.

The production target is enclosed in the inner conductor of the 1st horn. It is an isotropic graphite rod of 26*mm*-ϕ / 900*mm* long, enclosed in two layers of sleeves made of 2*mm*-thick graphite and 0.3*mm*-thick titanium alloy, respectively. Heat load on the target (69 kJ/spill) is cooled by compressed helium flow between the sleeves.

There is an Optical Transition Radiation (OTR) monitor in front of the target entrance window to monitor beam position and width on the target. It has 8 reflector Ti-alloy foils, stored in a rotating disk to automate exchange work.

Three magnetic horns will be operated to focus generated pions in the forward direction. They are composed of inner and outer conductors and large bus-bars made of aluminium. By applying 320kA pulsed current which synchronizes to the spill timing, toroidal magnetic field is generated between inner and outer conductors. To cool down the joule heat and also the energy deposit caused by the beam, water spray nozzles are installed inside of the horns. Upstream of the 1st horn, we will install a graphite baffle to guard the horn from the occasional miss-steered beam.

The magnetic horns and the baffle are supported from top by support modules, which are hanged from the wall of the helium vessel. 19 pieces of 2.2*m* thick iron cast blocks (~470 tons in total), and also 1*m*-thick concrete blocks will also be hanged from wall, covering the top of entire horn system for radiation protection. On top of the concrete blocks there is a service pit, where maintenance works by humans will take place.

For maintenance of horns and target, the iron and concrete blocks in the helium vessel will be handled remotely by twist-lock. After the horns and support modules are brought into a maintenance area, they are disassembled from top of the module through the shielding blocks. Remote exchange mechanism of the target from the 1st horn with a remote manipulator is also being developed. There is a waste-storage area, where broken horns and targets can be stocked in a long term.

Decay Volume and Beam Dump

TS, DV, and BD make up one big vacuum / helium vessel of about 1,700m^3 volume. At entrance of DV, there are three layers of collimators with 200*mm*-thick iron plates covered with plate coils. The cross section of DV has rectangular shape: At the entrance it is 1.4m x 1.7m, which gradually becomes larger towards downstream, 3.0m x 5.1m at the exit. It can accept the off-axis beam configuration between 2 and 3 degrees. DV is made of 16*mm*-thick iron plates, supported by stud anchors embedded in concrete wall. Inside of DV is covered with 40 channels of serially-connected plate coils.

The beam dump is located at downstream of the DV helium vessel, where a hadron absorber, the core of the beam dump, are installed together with water-cooled iron shields. The upper surface of the hadron absorber is 109*m* downstream of the production target. It is composed of 14 core modules and a frame supporting them. It has a size of 3.1*m* x 5.4*m* x 3.2*m*, and total weight of 70*t*. A core module is composed of 7 large extruded graphite blocks, fastened to an aluminium cast plate with cooling water paths in it. To keep flatness of 0.1*mm* for the cooling surface and for the loading surface, 7 graphite blocks are machined together at once. A design with multiple spring washers is adopted to fasten graphite and aluminium, to minimize the reduction of joint force, *i.e.* heat convection between them, by temperature rise at beam operation.

Muon Monitors and Neutrino Detectors

A muon monitor system is placed in a pit downstream of the beam dump. Since muons are produced together with neutrinos, profile centre of the muons can indirectly show that of the neutrinos. Although almost all hadrons are absorbed in the beam dump, muons with momentum greater than 5 GeV/c can penetrate it. There are two independent monitors, one is a semi-conductor diamond detector array (13 channels) and the other is ionization chamber tubes (7 channels x 7 tubes), covering 1.5*m* x 1.5*m* area. These monitors can provide muon profile in spill-by-spill basis with precision of a few *cm*.

We will have an experimental hall, located 280*m* downstream from the target. It has a cylindrical shape, whose inner diameter is 17.5*m* and depth is 33*m*. Two independent detector systems will be installed. One is placed on the beam axis for OA2.5, and the other is placed on the off-axis, at the direction of the far detector.

The purpose of the on-axis detector is to monitor direction and intensity of the neutrino beam. It has a grid layout, 7 units in X and 7 units in Y, where each unit consists of 10 layers of 100*mm* thick, 1*m* x 1*m* iron plates, sandwiched with scintillator bars. About 1.5 events per spill are expected for the centre unit, which can realize a few *cm* resolution for the centre of the neutrino beam.

The off-axis detector system consists of multiple detector components, such as fine-grained scintillator, π^0 detector, time projection chambers, calorimeter, and muon range detector. They are all enclosed in UA1 magnet, which will be imported from CERN this summer. Purpose of the detector is to measure spectrum of the neutrino at production. It also aims to measure contamination of the intrinsic electron neutrinos and to study electron-like background events caused by the inelastic interactions.

To predict the neutrino spectrum at the far site, it is vitally important to know near-to-far extrapolation ratio, which is dependent on the pion production on the target. T2K/NA61 experiment will take place at CERN [22], which will investigate proton and carbon thin/thick target interactions in 30 to 50 GeV region.

The far site detector, Super-Kamiokande (SK), is a large water Cherenkov detector with 22.5*kt* fiducial volume. It has capability to distinguish ν_e event from ν_μ event by using Cherenkov ring image pattern recognition. The timing information of the beam spill will be provided via GPS, which is used for the timing cut. With OA2.5, we expect 2,200 (1,600) ν_μ (charged-current) interactions per year, in case without oscillation.

T2K collaboration has a plan to submit a proposal to construct an intermediate detector at 2*km* downstream from the target [23]. At the distance, almost the same neutrino spectrum as the far detector will be measured as the un-oscillated spectrum. It will give a direct check for the prediction based on the off-axis detector at near site and T2K/NA61 experiment. The 2km detector system will be composed of a large cylindrical 9*m*ϕ x 13*m*-long water Cherenkov detector (100*t* fiducial volume), surrounded with a find-grained tracking detector at upstream and a muon range detector at downstream. We also have a plan to replace the former with a liquid Argon TPCs.

Construction and Production Status

The neutrino beam-line is under construction since FY 2004. Middle part of DV, which crosses to the 3NBT line, was already constructed in FY2005. Civil construction has recently been completed also for the primary beam-line, where installation of the normal conducting magnets will soon start from the preparation section. About half of

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Figure 5: Photographs of the neutrino beam-line components (a) the decay volume (b) SCFM doublets (c) 3rd horn, and (d) a core unit of the hadron absorber.

SCFM doublets has been fabricated and stored at Tokai campus. Installation will be started also in this FY.

Civil construction of the upstream of DV and TS is now under going. Parts of the huge helium vessel are ready at the factories, which will be transported and installed in this summer. Civil construction for the downstream of DV, BD, and the near detector hall is just starting, towards the completion in FY2008.

The 1st and 3rd horns have already been delivered, and long-term pulse operation test is now going on. Mock-up test for the 3rd horn with the support module is also going to take place. 2nd horn will be produced at US, which will be transported to KEK for further tests in next winter. 1st prototype of the target will soon be ready, and long-term helium gas flow test will be started.

Following to the success to make the 1st core module, all parts of the hadron absorber units will be produced within this FY. Assembling work will gradually be started from the end of this year.

Lots of tenders are now under going, to produce iron shield blocks in TS, DV collimantors, and helium vessel of the beam dump area, *etc*.

For the beam-line construction, KEK neutrino beam-line construction subgroup plays core roles. Meanwhile, international contributions also play essential roles for the crucial components of the beam-line, such as target and horn designs (UK/US), remote handling of target (UK), beam-window design (UK), OTR design and production (Canada), SCFM quench detection system (France), beam dump design (UK), beam monitors (US/Korea) *etc.*

SUMMARY AND FUTURE PROSPECTS

Various kinds of intense secondary beam lines are to be constructed at J-PARC, such as neutron / muon beam-lines in MLF, and intense kaon beam-lines in the Hadron Hall. As one of the main purposes of the project, a neutrino super-beam line is under construction to carry on T2K, Tokai-to-Kamioka neutrino oscillation experiment. Low-energy, quasi-monochromatic beam, produced with the off-axis beam configuration for the first time, will maximize possibility to detect excess of the ν_e-like events at the far site detector, caused by tiny ν_μ-to-ν_e oscillation. Although schedule is tight, we are making our best effort to complete the construction towards the commissioning scheduled in April, 2009.

It is to be noted that, if we are lucky to observe small, but finite ν_μ-to-ν_e oscillation signal, it is claimed that the CP phase (δ_{CP}) are going to be our observable, by upgrading the accelerator and the far detector [24]. This topic is to be further covered by another talk in this conference [25]. We are responsible to construct the beam-line with enough tolerance to promote neutrino physics for upcoming several tens of years.

REFERENCES

[1] The Mini-Boone Collaboration, Phys. Rev. Lett. **98**, 231801 (2007).

[2] Z.Maki, M.Nakagawa and S.Sakata, Prog. Theor. Phys. **28**, 870 (1962).

[3] Y.Fukuda et al. [Super-Kamiokande collaboration], Phys. Rev. Lett. **81**, 1562 (1998).

[4] S.Fukuda et al., Phys. Lett. **B539**, 179 (2002); Q.R.Ahmad et al. [SNO collaboration], Phys. Rev. Lett. **89**, 011301 (2002).

[5] Kamland Collaboration, hep-ex/0406035 (2004).

[6] M. Apollonio et al.[CHOOZ collaboration], Eur. Phys. J. **C27**, 331 (2003).

[7] M. H. Ahn et al [The K2K Collaboration], Phys. Rev. **D 74**, 072003 (2006).

[8] S.Yamamoto et al [The K2K Collaboration], Phys. Rev. Lett. **96**, 181801 (2006).

[9] Y.Itow et al., hep-ex/0106019 (2001).

[10] The joint project team of JAERI and KEK, JAERI-Tech 2000-03 (2000), KEK Report 99-5 (*in Japanese*); http://j-parc.jp/index.html

[11] T.Sasa, In Proc. of Global 2005, Tsukuba (2005); http://j-parc.jp/Transmutation/en/ads.html

[12] K.Hasegawa, this conference, THYAB02.

[13] T.Koseki, this conference, TUODKI01.

[14] Y.Miyake, Physica **B326**, 255 (2003).

[15] http://j-parc.jp/MatLife/en/index.html

[16] P05, http://j-parc.jp/NuclPart/Proposal_e.html

[17] P13, http://j-parc.jp/NuclPart/Proposal_e.html

[18] P14, http://j-parc.jp/NuclPart/Proposal_e.html

[19] J.K. Ahn et al. [E391a collaboration], Phys. Rev. D74, 051105(R) (2006).

[20] D. Beavis et al., Proposal of BNL AGS E-889 (1995).

[21] T.Ogitsu et al., IEEE Transactions on Applied Superconductivity **15**, 1175 (2005).

[22] http://na61.web.cern.ch/na61/

[23] T2K Collaboration, in preparation.

[24] J.Arafune, M.Koike, and J.Sato, Phys. Rev. **D56**, 3093 (1997).

[25] T.Kobayashi, this conference, FRZKI02.

 1-4244-0917-9/07/$25.00