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Secondary beam production in the nuclear and particle physics facility in J-PARC

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Abstract

At the Japan Proton Accelerator Research Complex (J-PARC), the world highest intensity secondary beams of kaons, pions, anti-protons, muons, and neutrinos will be produced by irradiating a target with the 50 GeV primary proton beam of 0.75 MW. Utilizing such high intensity secondary beams, various unique and interesting experimental studies in nuclear and particle physics can be carried out. We will describe the current R&D status of the target systems to be constructed in the Nuclear and Particle Physics Experimental Hall (NP-Hall) and the neutrino beam line of J-PARC. Some experimental studies proposed there will be also introduced.

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1. Introduction

The Japan Proton Accelerator Research Complex (J-PARC), being constructed in Tokai, will provide the highest-power hadron beams in the world. The 50 GeV Proton Synchrotron (50 GeV PS) at J-PARC will deliver a proton beam of the power as high as 0.75 MW. The proton beam will be extracted to two beam lines; one is the slow-extracted beam line connected to the Nuclear and Particle Physics Experimental Hall (NP-Hall), and the other is the fast-extracted beam line for neutrino experiments. Intense secondary beams of kaons, pions, anti-protons, muons, neutrinos can be produced and utilized for various nuclear and particle physics experiments. These facilities will play a leading role in the research fields in the world. In fact, 30 letters of intent (LOI) for nuclear and particle physics experiments with 478 authors in Europe, North America, and Asia were submitted in 2002 [1].

The present article introduces current designs of the NP-Hall and the neutrino beam line. The NP-Hall will play a role of a kaon factory. Unique and interesting studies with the kaon beams produced there will be carried out (Section 2). The current design status of the target system in the NP-Hall is described in Section 3. The neutrino experiment proposed at J-PARC is briefly introduced in Section 4, and the R&D work of the neutrino-production target is described in Section 5.

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2. NP-Hall

The current layout plan of the NP-Hall is shown in Fig. 1. The T1 target is only a source of intense secondary beams in the NP-Hall at the beginning. Thus, three secondary beam lines are installed at T1 in order that various physics experiments can be carried out efficiently.

The K1.8 beam line will be constructed on the left-hand side of T1 for the primary beam. K1.8 will deliver the world highest intensity of negative kaon (K^-) beam at the momentum from sub-GeV/c up to 2 GeV/c. A lot of hyperons (Λ, Σ, Ξ) and hypernuclei can be produced by the reactions like (K^-, K^+), (K^-, π). A hypernucleus is a nucleus where the hyperons are implanted. The hypernucleus has the strangeness quantum number, and we could add the third axis of the strangeness to the 'ordinary' nuclear chart. Compared with the ordinary nuclei, a limited number of hypernuclei have been produced, and thus we could explore the vast strangeness chart of the nuclides at J-PARC. Strangeness nuclear physics is the field related to the studies of the interactions of strange particles with nucleons and nuclear medium. Following distinct subjects have been proposed [1]: (1) spectroscopy of multi-strangeness nuclei, particularly double strangeness ($S = -2$) hypernuclei ($\Xi, \Lambda\Lambda$ hypernuclei), (2) hyperon–nucleon scattering, (3) high-resolution spectroscopy of $S = -1$ hypernuclei, including neutron-rich hypernuclei, (4) spectroscopic study of deeply bound kaonic nuclei, and (5) weak decay spectroscopy of hypernuclei. We could learn the meson–baryon, baryon–baryon, and many-body hadron interactions further through these spectroscopic studies. In particular, the interactions between baryons in short range would be revealed, where quark-gluon degree of freedom might be of importance. The knowledge is provided not only to nuclear physics but also to astrophysics. The equation of state (EOS) for dense matter determines most of the gross properties of neutron stars like the radii, masses, etc. Particularly, an important role of strange particles such as hyperons and K^- in neutron star cores is intensively discussed. The maximal radius and the cooling scenario of neutron stars should be described by the EOS taking the interactions of the strange particles into account. Therefore, information on the baryon–baryon (hadron–hadron) interactions obtained from the strangeness nuclear physics is essential for the discussion.

Intense, purified secondary beams ($K^{\pm}$, $\pi^{\pm}$, and $\bar{p}$) provided at K1.8 can be used for the hadron spectroscopic studies, Classifications of the hadron properties (mass, spin, isospin, parity, decay width/branching ratio) are essential to reveal the picture of the hadron as a composit system of quarks and gluons. In particular, a recent discovery of a new exotic state Θ^+, which is believed to be a penta-quark state comprising $dduu\bar{s}$, sheds light on the spectroscopic studies of exotic hadron states other than the normal qqq and $q\bar{q}$ states.

Another two kaon beam lines from T1 will be constructed in the opposite side of K1.8. One is a charged

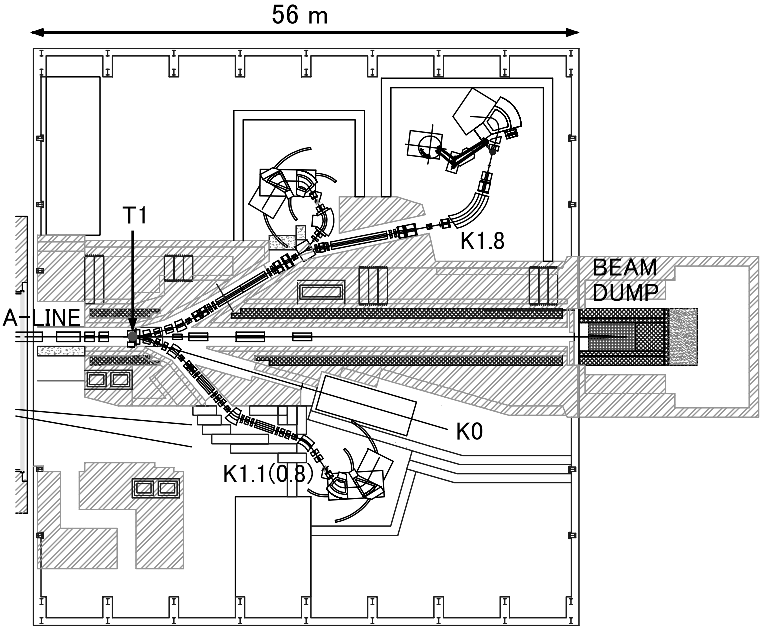

Fig. 1. Current layout plan of NP-Hall. The primary proton beam will be transported from the left hand side along A-line to the T1 target. Protons passing through T1 are absorbed at the beam dump.

kaon beam line, K1.1(0.8), and the other is a neutral kaon beam line, K0. K1.1(0.8) is designed and optimized to provide intense, purified $K^{\pm}$ beams up to 1.1(0.8) GeV/c. In K1.1(0.8), above-mentioned strangeness nuclear physics researches, particularly, the high-resolution spectroscopy of $S = -1$ hypernuclei, can be carried out.

The K1.1(0.8) and K0 beam lines will provide opportunities to proceed kaon rare decay physics. In the standard model of particle physics, the weak interactions of quarks are described in terms of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. One of the purpose of kaon decay physics is to investigate the validity of the standard model by means of rare decay or high-precision experiments and look for new physics beyond the standard model as a deviation. The unitarity condition of the CKM matrix can be tested in flavor changing kaon rare decay processes. Such kaon decay physics is closely related to CP violation physics and complementary to the B meson decay physics. Following experiments were proposed and intensively studied: (1) measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, (2) measurement of $K_L \rightarrow \pi^0 \nu\bar{\nu}$, (3) search for T-violation in $K^+ \rightarrow \pi^0 \mu\nu$, and (4) kaon decay spectrocopic studies. (1) and (2) are concerned with the determination of the CKM matrix elements and the transverse muon polarization in the (3) process would be a direct signature of the origin of CP violation beyond the standard model. In (4) one studies not only fundamental interactions but also QCD at low energy. All these experiments require intense beams with the momentum of 0.6–0.8 GeV/c for positive kaon (K^+) and 2 GeV/c in the average for neutral kaon (K_L).

3. T1 target

The 50 GeV proton beam of 0.75 MW is focused onto T1 with a spot as small as 1 mm in σ, assuming a Gaussian beam distribution at T1. The beam has the time structure of 0.7 s spill with 3.42 s repetition period. For the radiation safety reason, the target thickness of 30% interaction length is an allowed condition. Under these conditions, we require that T1 should be (1) thermally resistant, (2) a point-like source, (3) radiation hard, and (4) easily maintained. We thus consider water-cooled rotating nickel (or nickel-alloy) disks as the T1 target. As for the choice of target material, expected heat loads and temperature rises were compared for Pt, Ni, and Al at 3×10^{14} protons bombardment, as listed in Table 1. To first order, secondary particle yields in thin target are proportional to the interaction length of the target even when the secondary beam absorption is taken into account. Since a smaller target size is better for the secondary beam line optics, a heavier target seems advantageous. On the other hand, the heat load and temperature rise are larger in the case of heavier material. Ni is a moderate material in length and temperature rise. In any cases, the expected heat load is so large that a forced convection would be necessary. We adopted a water cooling system, as described below. It is advantageous that Ni is resistant against erosion in a moist environment.

We estimated the temperature rise of a rotating Ni disk target by using the ANSYS computer code of the finite element method. Here, we assumed the disk size of 240 mm in radius and 54 mm in thickness. We consider a cooling system with a water sink, as illustrated in Fig. 2. The rotation speed was chosen to be 85 rpm, which corresponds to 1 turn during a beam spill (0.7 s). We assume the water temperature of 30 °C and the heat transfer coefficient between the Ni disk and water equal to 1200 W/m^2/K. The outer part of the disk ($r > 60$ mm) was sinking under the water. The maximum temperature was estimated to be 94 °C at the beam spot, and the minimum temperature was 40 °C at the rotation axis. In the case of natural air convection, the maximum temperature was estimated to be ~600 °C at the beam spot, and the minimum temperature was ~400 °C at the rotation axis, where the heat transfer coefficient between the air and the disk surface was assumed to be $\alpha \sim 10$ W/m^2/K. If we could employ forced helium convection with $\alpha \sim 100$ W/m^2/K, the maximum (minimum) temperature can be ~150 (40) °C. However, forced convection over the disk surface is technically difficult. We therefore have chosen a water cooling system.

More detailed design of the T1 target is now in progress. The target is divided into five disks in beam direction in order to reduce the heat load per disk and increase the water cooling efficiency. Since not only the primary beam but also the secondary particles produced at the target deposit a fraction of their energy in the

Table 1
Estimated heat load and temperature rise for Pt, Ni, and Al as a target material when 3×10^{14} protons of 50 GeV bombard the target

	Length (mm)	Heat load (kJ)	Specific heat (J/g/K)	Temp rise (K)
Pt	31.5	78.8	0.14	8590
Ni	53.1	37.0	0.44	1340
Al	141.0	27.4	0.88	820

No convection is assumed. The target length of 30% interaction length is shown.

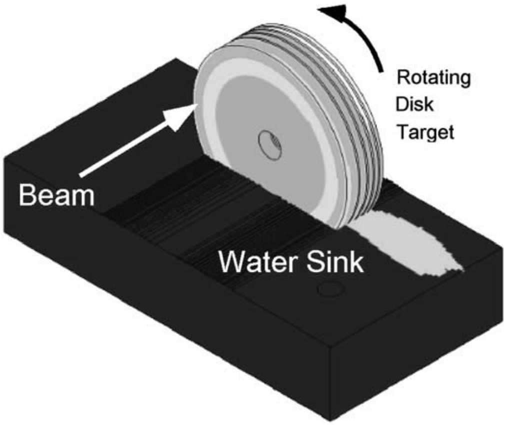

Fig. 2. Schematic view of a water cooled rotating disk target, T1.

target, the thickness of the disk is gradually thinner to equalize the heat deposit per disk. The gap between disks was taken to be 3 mm, which maintains the laminar water flow in the gap. Then, the rotation speed, the disk radius, and the depth of water were optimized to be 85 rpm, 140 mm, and 65 mm, respectively. The conceptual design and the maintenance scenario were almost completed. A proof model of the T1 target is fabricated next.

4. Neutrino experiment

A neutrino-oscillation experiment has been proposed at J-PARC [1,2]. Neutrino physics is one of the highlights at J-PARC. SuperKamiokande, which is the world-largest water Cherenkov detector, first established neutrino oscillation in the atmospheric muon neutrinos. The K2K experiment is the first long baseline neutrino experiment, sending the artificial muon neutrino beam produced at the KEK Proton Synchrotron (KEK-PS) toward SuperKamiokande at a distance of 250 km, and is being performed and confirmed a reduction of the muon neutrino flux from that expected in the case of no oscillation [4], as consistent with the atmospheric neutrino observation [3]. Neutrino oscillation takes place when neutrinos have non-zero masses and mixings, and is thus a phenomenon beyond the Standard Model. In the three generation scheme, lepton mixing is described by a unitary 3 × 3 matrix, so-called Maki–Nakagawa–Sakata (MNS) matrix. These elements can be expressed with three mixing angles $(\theta_{12}, \theta_{23}, \theta_{31})$ between weak eigenstates and mass eigenstates, one CP-violating phase (δ). The oscillation probability is written by relevant mixing angle and two independent mass squared differences $(\Delta m_{ij}^2 = m_i^2 - m_j^2, i, j =, 2, 3)$. Recent remarkable progress of neutrino physics in the world confirmed the oscillations in the ν_μ disappearance, solar neutrino (ν_e), and reactor neutrino ($\bar{\nu}_e$) measurements, with constraints on Δm_{12}^2 and Δm_{23}^2 with a large mixing angle region. Then, the next-generation neutrino experiment is required to determine those oscillation parameters with high accuracy. At J-PARC, following three main goals are pursued; (1) discovery of $\nu_\mu \to \nu_e$ appearance, determining θ_{13}, (2) precision measurements of oscillation parameters in the ν_μ disappearance, Δm_{23}^2 and $\sin^2 2\theta_{23}$, at the error level of 10% and 1%, respectively, and (3) search for sterile components in the ν_μ disappearance. In particular, determination of the θ_{13} parameter is indispensable for a future discovery of CP-violating phase δ.

5. Neutrino target

For the neutrino experiment, the proton beam will be extracted from the 50 GeV PS within 5 μs every 3.53 s (fast extraction). Eight bunches are contained in the 5 μs pulse. A plan view of the fast-extracted beam line is shown in Fig. 3. The proton beam is transported to the target station, where secondary pions are produced and a neutrino beam, created through the process of a pion decaying into a muon and a muon neutrino, is directed toward the SuperKamiokande at a distance of 295 km. Graphite is chosen as a target material since it is thermally resistant against the instantaneous temperature rise by hitting of the primary beam in a short pulse and its low density is advantageous to minimize the heat deposit maintaining the pion yield.

First we optimized the target diameter. A Monte Carlo simulation with GEANT [6] was carried out for the primary beam size fitted to the target diameter, including the multiple scattering effect and the absorption effect. It was found that the pion yield was not very sensitive to the target diameter less than 30 mm. Total energy deposit was approximately 60 kJ.

The thermal stress was analytically estimated from the maximum temperature rise (T_0) in the target, which is expressed as

$$\sigma_{eq} \leqslant \frac{2 - \nu}{3(1 - \nu)} E \alpha T_0, \qquad (1)$$

where σ_{eq}, ν, E, and α represent the equivalent stress, the Poisson ratio, the Young modulus, and the linear expansion coefficient, respectively. In the case of the IG-43 (TOYO-Tanso) graphite of 30 mm diameter and 900 mm length, σ_{eq} was estimated to be 7.42 MPa at T_0 = 196 K, while its tensile strength was 37.2 MPa. The safety factor was estimated to be 3.51 if one took a fatigue factor 0.7 after 10^7 heat cycles. It is found that the diameter has to be greater than 28 mm in order to maintain the safety factor >3.

Next we estimated a necessary cooling power. We considered a simple model of a water flow in a tube sur-

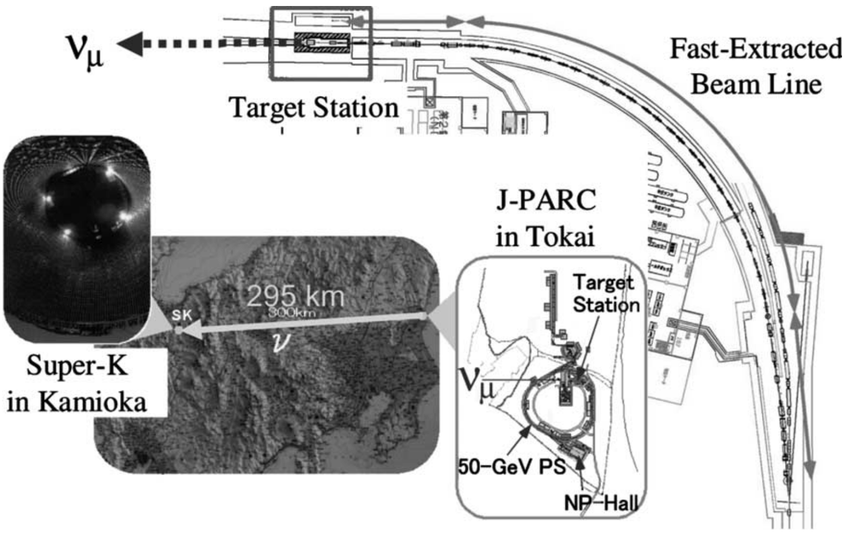

Fig. 3. Fast-extracted beam line for the neutrino experiment.

rounding the target rod to remove the heat. Assuming the radial symmetry and ignoring the heat transfer along the beam axis, time evolution of the temperature at r can be calculated for given water flow rate (F) and heat transfer coefficient between the target and water (h) solving the following differential equation:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial^2 r} + \frac{1}{r}\frac{\partial T}{\partial r}\right), \tag{2}$$

at a boundary condition of

$$\left(\frac{\partial T}{\partial r}\right)_{r=R} = -\frac{h}{\lambda}(T_{r=R} - T_{\mathrm{water}}) \tag{3}$$

and a given initial temperature distribution. Here, a, λ, R, and T_{water} denote the thermal diffusity, the thermal conductivity, the target radius, and the water temperature. A distribution of the energy deposit in the target was given by the MARS computer code [7]. Here, we took the radial distribution at the maximum energy deposit along the beam. The region of F and h to satisfy the maximum surface temperature less than 100 °C can be constrained. On the other hand, it is empirically known that h can be obtained by the following equation:

$$h = \frac{Nu \times \lambda_{\mathrm{water}}}{d}, \tag{4}$$

where Nu, λ_{water}, and d are the Nusselt number, the heat conductivity of water and the equivalent diameter of the water tube cross section. At the condition of the flow speed fixed at 1.0 m/s in order to reduce the erosion effect, h can be calculated as a function of F and the surface temperature. The applicability of Eq. (4) was demonstrated at the flow rates of 8.9 ℓ/min and 12 ℓ/min with the test target system, as illustrated in Fig. 4, where the Joule heat is supplied to the graphite target from the electric power supply and the target surface temperature and the water temperature were measured to obtain the heat transfer coefficient [5]. Finally, we obtained the necessary water flow rate $F > 12$ (10) ℓ/min for the target diameter of 28 (30) mm at the flow speed of 1.0 m/s to satisfy the maximum surface temperature less than 100 °C.

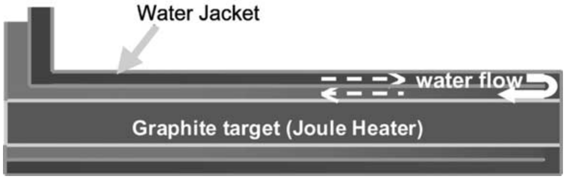

Fig. 4. Longitudinal cross section of a graphite rod with a water-cooling jacket.

Detailed designs are still under progress. Particularly, radiation damages of the graphite target must be taken into consideration. Irradiation of the 50 GeV protons on the target will be as high as 0.3 dpa in a year operation [8]. The thermal conductivity of graphite will be reduced to 10–20% or less of its original value [9]. In addition, a change of the graphite target size has been reported [9]. For a shrinkage of the target rod, a realistic estimation of the heat transfer coefficient from the target to the coolant is necessary.

6. Summary

High-power target systems to produce high-intensity secondary particle beams are being designed for the

Nuclear and Particle Physics Facility at J-PARC. A water-cooled rotating Ni disk target is designed and being developed for the slow-extracted proton beam to produce intense kaon beams in NP-Hall. Utilizing the kaon beams, various experimental studies in strangeness nuclear physics and kaon decay physics will be carried out. A neutrino-oscillation experiment has been proposed at J-PARC. Conceptual design for a neutrino-beam source using a fast-extracted beam is in progress. A graphite-rod target is considered, and it is expected to be resistant against the thermal stress with a safety factor 3. The flow rate of cooling water to keep the surface temperature of the graphite rod less than 100 °C was estimated to be greater than 12 (10) ℓ/min in the case of the target diameter of 28 (30) mm. For a realistic design, the radiation damage effects of graphite, such as changes of the size and/or the thermal conductivity, have to be taken into consideration.

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References

[1] Letters of Intent for Nuclear and Particle Physics Experiments at the J-PARC, edited by the J-PARC Project Office, KEK, Feb. 2003, J-PARC 03-6; See also http://www-ps.kek.jp/jhf-np/LOIlist/LOIlist.html.

[2] The latest version of the LOI for the Neutrino Oscillation Experiment at J-PARC may be available from http://neutrino.kek.jp/jhfnu/.

[3] Y. Fukuda et al., Phys. Rev. Lett. 85 (2001) 3999.

[4] M.H. Ahn et al., Phys. Rev. Lett. 90 (2003) 041801.

[5] S. Ueda, Master thesis, Kyoto University, 2004.

[6] R. Brun et al., CERN DD/EE/84-1 (1987).

[7] N.V. Mokhov, The Mars Code System User's Guide, Fermilab-FN-628(1995), MARS Code Developments, Benchmarking and Applications, Fermilab-Conf-00-066 (2000);
N.V. Mokhov et al., MARS Code Developments, Fermilab-Conf-98/379 (1998);
N.V. Mokhov et al., LANL Rep. LA-UR-98-5716 (1998); nucl-th/9812038 v2 16 December 1998;
O.E. Krivosheev, N.V. Mokhov, A New MARS and its Applications, Fermilab-Conf-98/43 (1998).

[8] B.T. Kelly, B.J. Marsden, K. Hall, IAEA-TECDOC-1154, IAEA, Vienna, Austria, 2000;
V.S. Barashenkov, V.D. Toneev, Interaction of Particles and Atomic Nuclei of High and Superhigh Energies with Nuclei, Atomizdat, Moscow, 1972, in Russian.

[9] T. Tanabe et al., Fusion Eng. Des. 29 (1995) 428;
T. Maruyama, M. Harayama, J. Nucl. Mater. 195 (1992) 44.