J-PARC Facilities and Physics

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Abstract

The J-PARC (Japan Proton Accelerator Research Complex), which consists of LINAC, RCS and MR synchrotron, has successfully produced wide variety of secondary beam (neutrons, muons, pions, kaons, and neutrinos) by steady commissioning since November 2006. There are three experimental facilities, and for nuclear and particle physics, ten experiments are approved in a hadron physics facility, and one experiment is approved in a neutrino physics facility. The facilities and status of these approved experiments in J-PARC are described in this paper.

Key words: Spectrometers, Beam characteristics, Hyperons, Exotic Baryons, Standard Model
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1. ACCELERATOR AND EXPERIMENTAL FACILITIES

The J-PARC [1] is an intenational research facility aiming for 1MW class power, by the joint project of JAEA and KEK. The proton accelerator comprises the 181 MeV (currently being upgraded to 400 MeV) LINAC , 3GeV Rapid Cycle Synchrotron (RCS) , and 50 GeV (30 GeV in phase-1) Main Ring Synchrotron (MR) (See figure 1). In order to achieve the lowest beam loss, the trajectry of the beam is controlled precisely upto several tens micron meters owing to the systematic production and calibration of the monitors [2]. In J-PARC, three experimental facilities are in operation; materials and life science facility (MLF), neutrino facility (NU), and hadron physics facility (HD). Since November 2006, when all the accelerator and monitoring devices [3] for LINAC are ready, J-PARC beam commissioning started. In January 2007, 181 MeV acceleration has succeeded, and commisioning of RCS and MR followed. Then productions of neutrons, muons, kaons, and neutrinos succeeded first in May, September 2008, February, and April 2009, respectively. After summer shutdown in 2010, slow extraction experiment (beginning with the E19 experiment) in the HD facility is aiming for operation with more than 5 kW power and more than 15 % duty factor, and the fast extraction experiment (namely T2K experiment) in the NU facility is running over 100kW toward the design power.

2. NUCLEAR AND PARTICLE PHYSICS

Currently (as of the 10th Program Advisory Committee (PAC) for nuclear and particle experiments, held in July 2010), ten experiments are approved in the hadron physics facility (See figure 2), and one experiment (T2K experiment, for neutrino oscillation) is approved in the neutrino facility. The approval mechanism of experiments in J-PARC is following. After the 1st stage approval (where scientific merit is high), the 2nd stage approval is given as a green light for each of these eleven experiments to proceed, based on

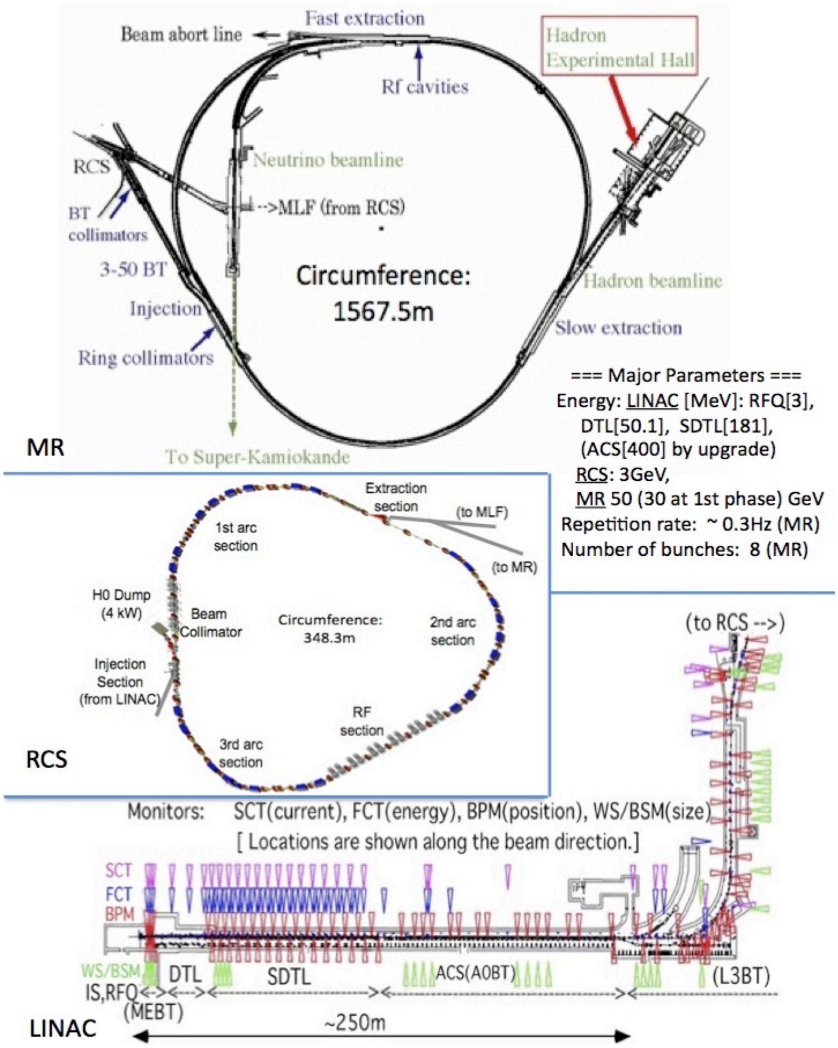

Fig. 1. J-PARC Accelerator Facilities

the technical achievability, the reliability of cost estimate, and the other various aspects of feasibility. Table 1 shows experiments which have the 2nd stage approvals as of the 10th PAC. In the following section, evaluations of the experiments are described, based on the each proposal [4] submitted to the PAC.

2.1. *Hadron Physics Experiment with Strangeness; Exotic state containing Kaons or Hyperons*

2.1.1. *The E27 Experiment*

The E27 experiments is one of the most recent approved experiment (approved at the 10th PAC in July 2010). The purpose of the experiment is to produce and study the K^-pp bound state by using high intensity of π beam, via $d(\pi^+, K^+)$. By increasing the incident momentum at around 1.5 GeV/c, a lot of $\Lambda(1405)$'s are possible to be produced. Then the formation of a $\overline{K}$ nucleus is expected with the $\Lambda(1405)$ as a doorway. For the experimental method, a liquid deuterium target (which is common system with E19 experiment) is used to produce K^-pp system. Two-proton tagging method is applied to remove quasifree hyperon production background.

2.1.2. *The E19 Experiment*

The E19 experiments will measure exotic particle through $p(\pi^-, K^-)X$ reaction, where X is expected to be Θ^+ pentaquark. The first observation of the Θ^+ baryon with positive strangeness $S = +1$ was reported through photon induced reaction and has been

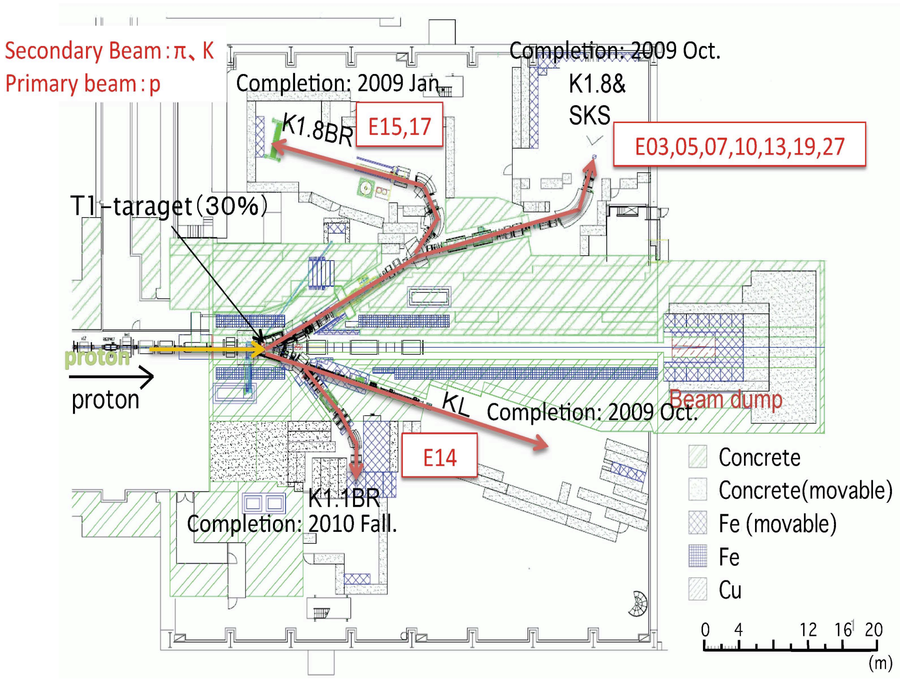

Fig. 2. Hadron Experimental Hall (Hadron Physics Facilities)

supported by several collaboration [5] . As statistical limit in positive results and null results are also reported, therefore confirmation of the existence (or non-existence) of the Θ^+ is still controversial [6]. Especially the meson induced reaction using a proton target is still unique to KEK-PS and J-PARC. In J-PARC, experiment will be performed at the K1.8 beam line. The π^- beam with 1.87, 1.92 and 1.97 GeV/c momentum will be used to a liquid hydrogen target of 12.5 cm thickness (re-use of the one constructed for the KEK-PS E559 experiment [7]). The momentum of scattered K^- is measured in the range of 0.7 to 0.95 GeV/c with SKS spectrometer [8]. The intensity of the π^- beam is determined by the rate capability of the detector system and is assumed to be 1×10^7 per 4 second cycle. Required intensity of primary proton beam to achieve this is less than 10 % of the design intensity of J-PARC. The SKS spectrometer has a capability to measure the width of Θ^+ with a highest resolution, which is estimated to be 2.5 MeV. If the target is irradiated with 4.8×10^{11} pions for each momentum (which is 100 times more than E522) and assuming $1.9\mu b/sr$ for production cross section of Θ^+, we will obtain 1.2×10^4 events for the momentum setting. The E19 experiment has started beam commissioning run since October 2009, and during calibration run the SKS spectrometer showed Σ^- reconstruction with $\Delta M = 1.66 \pm 0.05$ (FWHM) MeV in $\pi^- p \rightarrow K^+ \Sigma^-$ reaction. E19 is scheduled to begin data taking in October 2010.

2.1.3. *The E05 Experiment*

The E05 experiment is proposed to get spectroscopic information Ξ-hypernucleus, ${}^{12}_{\Xi}Be$, through ${}^{12}C(K^-, K^+)$ reaction. The Ξ single particle potential obtained from the observation of Ξ-hypernucleus states gives not only the information of ΞN interaction but also insight into the high-density hadronic matter with strangeness. Experimental method and apparatus are following. Missing mass, M, defined as $M^2 = (E_B + m_T - E_S)^2 - (\overrightarrow{p}_B - \overrightarrow{p}_S)^2$, where suffixes B, T, and S mean beam, target and scattered particles, respectively. Beam momentum is analyzed by $QQDQQ$ magnets and four sets of tracking detector in the beam line, and expected momentum resolution, $\Delta p/p$, is 1.4×10^{-4} in rms. Scattered beam (K^+) momentum is measured by the SKS magnet with some modification. Because K^+ momentum corresponding to the production of Ξ-hypernuclei is around 1.3 GeV/c and the SKS maximum magnetic field of ∼2.7 T does not allow to put the central ray at 1.3 GeV/c, additional dipole magnet with ∼1.5 T will be placed at the entrance of the SKS magnet. This is called as "SksPlus" spectrometer, which has a solid angle of ∼30 msr with angular range upto 10 degrees, and momentum resolution, $\Delta p/p$, is 0.17 % (FWHM). As missing mass energy resolution is mainly determined by the K^+ spectrometer and energy loss straggling in the target, the maximum target thickness is 5-6 g/cm^2 to keep the resolution within the acceptable level, 3MeV. For the number of K^-, we can expect 3.7×10^{10} (/day) for 1.4×10^6 (/spill) when we choose flat-top length of 0.8 second. And the yield of ${}^{12}_{\Xi}Be$ is estimated to be 6.3 (/day) ∼190 (/month), which means we need ∼1 month of data taking.

2.1.4. *The E13 Experiment*

The E13 experiment is to study structure of several light hyper nuclei (${}^{4}_{\Lambda}H$, ${}^{7}_{\Lambda}Li$, ${}^{10}_{\Lambda}B$, ${}^{11}_{\Lambda}B$, and ${}^{19}_{\Lambda}F$) by high-precision spectroscopy. Newly-constructed large germanium detector array is dedicated for detection of γ rays from hypernuclei. Exited states of these hypernuclei are produced by (K^-, π^-) reaction. The purposes of the experiment are

(1) the first precise measurement of the Λ-spin-flip B(M1) to investigate the magnetic moment of a Λ in a nucleus, and (2) further study of interaction to establish the spin-dependent ΛN interaction strengths and to clarify the $\Lambda N - \Xi N$ coupling force as well as the charge symmetry breaking effect in ΛN interaction. For the experimental setup, K^- beam of 1.5 GeV/c is used at K1.8 beam line where two-stages mass separators provide lower π/K ratio (less the 0.5) to minimize the radiation damage to the germanium detectors. The kaon beam is irradiated to various targets; liquid ^4He (2.0 g/cm^2), $^{nat}Li_2O$ (17.2 g/cm^2 for ^7Li), ^{10}B metal (20 g/cm^2), ^{11}B metal (20 g/cm^2), and ^{19}F in teflon (15.2 g/cm^2 for ^{19}F) . Just upstream and downstream of the target, aerogel Cerenkov detectors are used to idendify kaons in beam and pions in scattered particles. Scattered pions are momentum-analyzed by the SKS magnet and tracking chambers. Including energy loss effect in the thick target (typically 20 g/cm^2), expected mass resolution is 5.9 MeV (FWHM), which is enough to tag hypernuclear bound state region. The γ rays from hypernuclei are detected Ge detector, which is surrounded by PWO counter for background suppression, and estimated photo-peak efficiency is about 5 % for the realistic source point distribution in the Li_2O target. About 1000 hours of K^- beam time is requested for the physics purpose described above, when assuming beam intensity is 0.5×10^6 per spill for 1.5 GeV.

2.1.5. *The E03 Experiment*

The E03 experiment is to perform the first measurement of Ξ-atomic X rays from Fe target at K1.8 beam line. Physics interest is in Baryon-Baryon interaction at $S = -2$ sector, which is important to understand the properties of neutron stars of which density is so high that significant amount of hyperons is expected to appear in the core. Measurement of X-ray from Ξ-atom is promising approach to study optical potential in nuclei; this approach has been successfully used in cases of negative charged hadrons (π^-, K^-, $\overline{p}$, and Σ^-). The X-ray energy shift gives information on the real part of the optical potential, while X-ray width and yield are relevant to the imaginary part. K^- in the beam is identified by time of flight counters and an aerogel Cherenkov counter. The scattered K^+ particles are detected by KURAMA spectrometer, which has large acceptance of 0.2 sr, which allows to maximize the yield of Ξ^-. X-ray is detected by Hyperball-J, which consists of about forty Ge detectors surrounded by fast PWO counters for background suppression. Assuming 1.8 GeV/c K^- beam with an intensity of 1.4×10^6 per spill (4 sec/spill with 1.2 seconds flat-top) for 800 hours, expected X-ray yield is 2500 counts in 7.5×10^5 stopped Ξ^- on Fe target. The 2500 counts give statistical energy shift accuracy of better than 0.04 keV (0.05 keV with systematic errors), which is sensitive enough to observe expected energy shift (1keV) with reasonable accuracy.

2.1.6. *The E07 Experiment*

The E07 experiment is for a systematic study of double strangeness nuclei with 10 times higher statistics than previous experiment (KEK-E373 [9]). Expectation is to observe 10^4 stopping Ξ^- hyperons in the emulsion via quesi-free (K^-,K^+) reactions on a diamond target. And this will provide one thousand events showing formation of double strangeness nuclear systems, then among them we will detect one hundred nuclear fragments with double strangeness to make a chart of $S = -2$ nuclei. Requested beam is 600 hours with 3×10^5 K^- per spill. Experimental setup is following: (K^-,K^+) reaction,

$K^- + "p" \rightarrow K^+ + \Sigma^-$, is detected by KURAMA spectrometer. Both (1) between the target and the emulsion and (2) just after the emulsion, silicon strip tracking detectors are placed to tag the Ξ^- produced in the target and stopped in the emulsion. Advanced detectors and automated scanning system enable us to obtain ten times more events than KEK-E373 within a few years of data analysis.

2.1.7. *The Other Approved Experiments*

Other approved experiments are: E10 experiment for Production of Neutron rich Λ-hypernuclei with the double charge-exchange reaction, E15 experiment as a search for deeply-bound kaonic nuclear states by in-flight $^3He(K^-, n)$ reaction, and E17 experiment for precision spectroscopy of Kaonic ^3He $3d \rightarrow 2p$ X-rays.

2.2. *Elementaly Particle Physics Experiment*

2.2.1. *The E14 ("KOTO") Experiment*

The E14 experiment (KOTO experiment) aims to discover a CP-violating decay mode, $K^0_L \rightarrow \pi^0 \nu\overline{\nu}$. The CP-violating parameter, η, in the CKM matrix can be determined from the branching ratio of the decay with a theoretical uncertainty of 1-2 %. The branching ratio is expected to be $(2.8 \pm 0.4) \times 10^{-11}$ in the Standard Model prediction. The signature of the decay distinct from other backgrounds are that only two gammas from a π^0 exist and the transverse momentum of the π^0 is large due to the missing neutrinos. A hermetic detector ensures only two gammas and nothing else, and the small-diameter beam enables the π^0 reconstruction to constrain the decay vertex of the π^0. The collimators need to be designed to reduce the ratio of the halo-neutron and K_L fluxes to be 7×10^{-4}, which is one of the key performances to determine the sensitivity of the experiment. The beam line was designed to realize a small-cross-section neutral beam with a solid angle of 7.8 μsr using two collimators and a sweeping magnet. The length of the beam line is 20 m, where short-lived particles are decayed. Only gammas, neutrons, and K_L's are remained at the beam line exit. The gamma flux is reduced with a 7-cm-long lead absorber at the upstream of the beam line. The initial goal is to make the first observation of the decay with the expectation to observe 3.5 Standard Model events with 1.8×10^{21} protons (equivalent to 2×10^{14} (protons/spill) $\times 3 \times 10^7$ seconds of running, where 3.3 sec/spill) on target in total.

2.2.2. *The E11 ("T2K") Experiment*

The E11 experiment (T2K experiment) is a long baseline neutrino oscillation experiment, using fast extracted proton beam from MR synchrotron and existing Super-Kamiokande (SK) detector. One of the main goals of this experiment is the discovery of $\nu_\mu \rightarrow \nu_e$. A factor of 20 improvement in sensitivity over the present upper limit is possible, then the goal is to extend the search down to $\sin^2 2\theta_{13} \sim \sin^2 2\theta_{\mu e} > 0.008$. To achieve this goal, it is requested to have total integrated beam power larger than $0.75MW \times 15000h$ at any proton energy between 30 and 50 GeV. The SK detector is the world largest water Cherenkov detector as the far detector, and has excellent energy resolution and e/μ identification capability in low energy neutrino reaction, backed by about twenty years of experience of the water Cherenkov detector. The T2K accumulated neutrino beam data corresponding to 3.35×10^{19} PTO (proton on target) with

Table 1
Experiments in J-PARC approved at the PAC (approved both as the 1st and 2nd stage (for the meaninig of "stage", see text) after the 10th PAC held in July 2010)

Experiment	(Purpose of Experiment)	Location
E19	High-resolution Search for Θ^+ Pentaquark in $\pi^- p \to K^- X$ Reactions	K1.8
E27	Search for a nuclear Kbar bound state $K^- pp$ in $d(\pi^+, K^+)$ reaction	K1.8
E13	Gamma-ray spectroscopy of light hypernuclei	K1.8
E10	Production of Neutron-Rich Lambda-Hypernuclei with the Double Charge-Exchange Reaction	K1.8
E03	Measurement of X rays from Ξ Atom	K1.8
E07	Systematic Study of Double Strangeness System with an Emulsion-counter Hybrid Method	K1.8
E05	Spectroscopic Study of Ξ-Hypernucleus, ${}^{12}_{\Xi}Be$, via the ${}^{12}C(K^-, K^+)$ Reaction	K1.8
E15	A Search for deeply-bound kaonic nuclear states by in-flight ${}^3He(K^-, n)$ reaction	K1.8BR
E17	Precision spectroscopy of Kaonic ${}^3He$ $3d \to 2p$ X-rays	K1.8BR
E14	$K_L \to \pi^0 \nu \overline{\nu}$ Experiment at J-PARC	K0
E11	Tokai-to-Kamioka (T2K) Long Baseline Neutrino Oscillation Experiment	Neutrino

beam operation until June 26 in 2010, and 22 neutrino events have been observed [10] by the SK in the analysis so far with data accumulated through the middle of May.

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