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J-PARC kaon and muon programs

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Summary. — J-PARC has recently commenced operations. A variety of programs in particle and nuclear physics are planned to be conducted here. Among these, the kaon and muon programs are introduced in this presentation.

PACS `11.30.Hv` – Flavor symmetries.
PACS `14.40.Df` – Strange mesons.
PACS `14.60.Ef` – Muons.

1. – Introduction

The J-PARC, Japan Proton Acceleration Research Complex (J-PARC), is a joint project between the Japan Atomic Energy Agency (JAEA) and the High Energy Accelerator Research Organization (KEK) and is a new and exciting accelerator research facility. The ultimate goal of the project is to generate a megawatt-class high-power proton beam at both 3 GeV and 30 GeV. In this facility, various types of secondary particles such as neutrons, muons, kaons, and neutrinos are produced in proton-nucleus reactions for use in materials and life science experiments as well as particle and nuclear physics experiments.

J-PARC is composed of three accelerators, as illustrated in fig. 1. The linac accelerates the beam (H^-) up to 181 MeV. Then, the beam is transferred to the Rapid Cycle Synchrotron (RCS), a booster after passing through a foil to strip the H^- beam of electrons. In the RCS, the proton beam is accelerated to 3 GeV and extracted by fast kickers to the Material Life Science Facility (MLF), an experiment facility where muons and neutrons are produced on graphite and mercury targets.

Part of the proton beam accelerated in the RCS is transfered to the Main Ring (MR), another synchrotron.The MR accelerates the beam to 30 GeV and supplies it to a neutrino facility by fast extraction using a series of kickers and to a particle and nuclear physics facility by slow extraction using electrostatic septa and septum magnets.

From 2008, J-PARC began producing four different types of secondary beams on schedule. The first was the neutron beam in May 2008 and the second was the muon beam in September 2008 at the MLF. Kaon beam production was successfully carried out

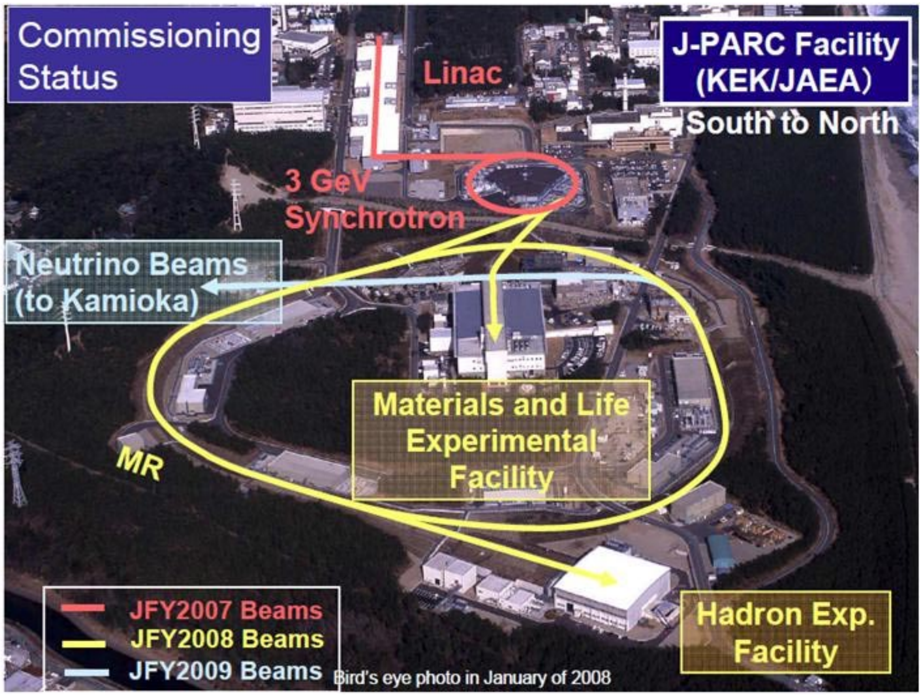

Fig. 1. – J-PARC accelerators.

in May 2009 by using a proton beam extracted from the MR. Neutrino production was then confirmed in April 2009 by using the MR proton beam. Currently, the accelerator group is attempting to improve the beam power while minimizing the beam loss; this should lead to less difficulty in machine maintenance in the future.

The achieved beam powers are listed in table I. Figure 2 shows the expected beam power improvement. It is planned to upgrade the linac to accelerate H^- up to 400 MeV in 2013, thus enabling a further improvement in the beam power in both the RCS and the MR.

As already mentioned above, two extraction methods are used at the MR. One is the fast extraction method that supplies the proton beam all at once to the neutrino experiment (T2K) without destroying the bunch structure necessary for beam acceleration. The other is the slow extraction method that supplies the proton beam to produce sec-

Table I. – *J-PARC beam power as of February 2010.*

Accelerator	Energy	Power	Proposed experiments
Linac	181 MeV	113 kW	neutron EDM
RCS	3 GeV	120–300 kW	muon/neutron physics experiments
MR Fast Extraction	30 GeV	50–100 kW	neutrino program
MR Slow Extraction	30 GeV	1.6 kW	secondary beam experiments

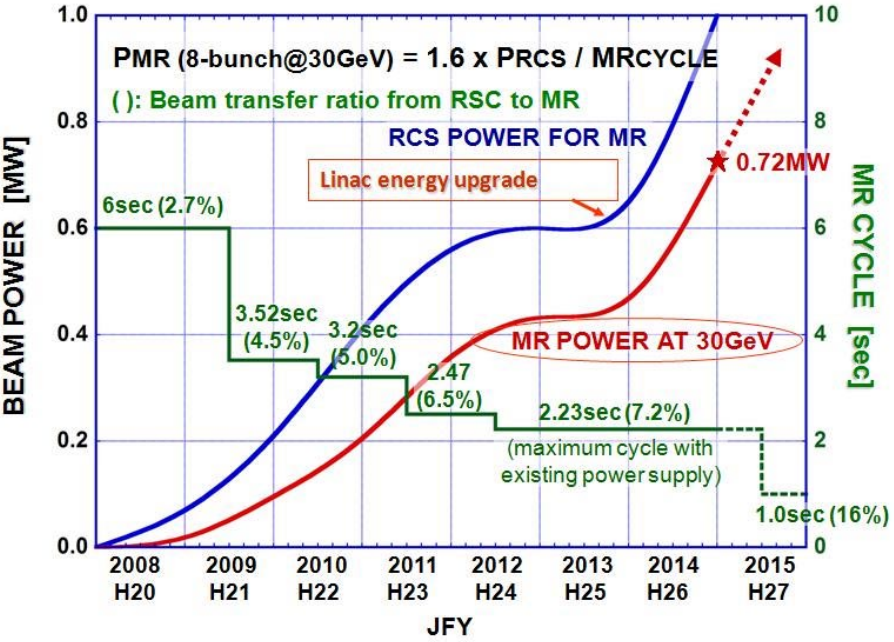

Fig. 2. – Expected beam power improvement of J-PARC.

ondary particles other than neutrinos. In this extraction mode, a part of the beam in the MR is extracted turn-by-turn in order to suppress event overlap in the experiments. Most of the experiments carried out using this extraction mode require a beam with a flattened time structure. Due to this, the acceleration RF is switched off during beam extraction. An exception is the μ-e conversion search experiment that is described later. This experiment requires a slowly extracted proton beam without destroying the bunch structure in the MR. This method is called bunched-slow extraction. The fast and normal slow extractions have already been tested and their performance is being improved, whereas the bunched-slow extraction for the μ-e conversion experiment needs to be proved operationally.

2. – Kaon programs

Two particle physics experiments using the kaon beam have currently been proposed at J-PARC. One is the TREK experiment to measure the T-violating muon P_T in $K^+ \to \pi^0\mu^+\nu_\mu$ decays, and the other is the KOTO experiment to study $K_L \to \pi^0\nu\bar{\nu}$ decays.

2·1. *TREK*. – Time-Reversal violation Experiment with Kaons (TREK) aims to measure a T-odd K^+ decay parameter, the transverse muon polarization P_T in $K^+ \to \pi^0\mu^+\nu_\mu(K_{\mu3})$ decays, with a sensitivity of 10^{-4} [1], where P_T is defined as

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}\,.$$

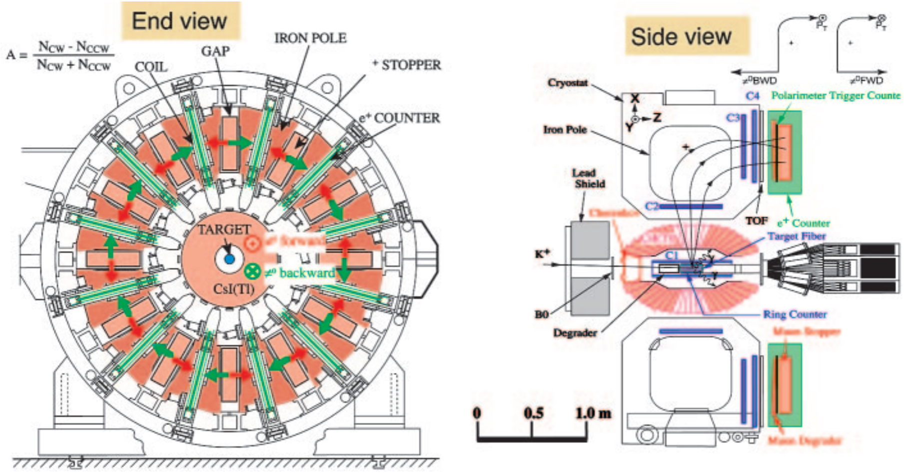

Fig. 3. – TREK spectrometer.

Here, $p_{\pi^0,\gamma}$ and p_{μ^+} denote the π^0 (or γ) and μ^+ momenta, respectively, and σ_μ denotes the spin of the μ to be measured using the active polarimeter equipped in the setup. The effects of final-state interactions on P_T are expected to be as small as 10^{-5}. In addition, the Standard Model (SM) contribution to P_T is calculated to be smaller than 10^{-7}. Thus, P_T measurement in the region of $10^{-3} \sim 10^{-4}$ can serve as a sensitive probe of CP violation in the SM because T violation is equivalent to CP violation according to the CPT theorem.

Figure 3 shows a schematic of the TREK spectrometer. The spectrometer is composed of an active polarimeter to measure muon polarization, a tracking system to track μ^+ and to measure its momentum, a CsI(Tl) calorimeter surrounding the target region to identify π^0 (or γ) and to measure its energy. In this experiment, the magnetic field to measure muon momentum is applied in the azimuthal direction parallel to the P_T component and $cw - ccw$ positron asymmetry in the azimuthal direction is measured depending on whether π^0 (or γ) is emitted forward or backward. The most recent measurement of P_T was carried out at the KEK proton synchrotron, as the E246 experiment. This experiment provided the best limit of $P_T = 0.0017 \pm 0.0023\ \text{(stat)} \pm 0.0011\ \text{(syst)}$ known thus far [2].

Currently, the construction of the beam line and the detector system is in progress with the goal of commencing data acquisition in 2012. It is necessary to realize a beam power of more than 100 kW to achieve the target sensitivity of 10^{-4} for two years running.

2·2. *KOTO*. – K0 at TOkai (KOTO) is an experiment to measure the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$ that is predicted by the SM with a small theoretical uncertainty at $(2.8 \pm 0.4) \times 10^{-11}$ [3]. This process is a CP-violating process and the branching ratio is proportional to the square of η, which is one of the Wolfenstein parameters determining the imaginary component of the CKM matrix. Thus, the η parameter can be determined through this measurement with a small ambiguity thanks to the small theoretical uncertainty of the order of 1–2% [4]. It is also important to note that, because the SM contribution to this decay mode is small, the measurement is sensitive to a new physics beyond the SM as predicted by many theoretical models [5, 6].

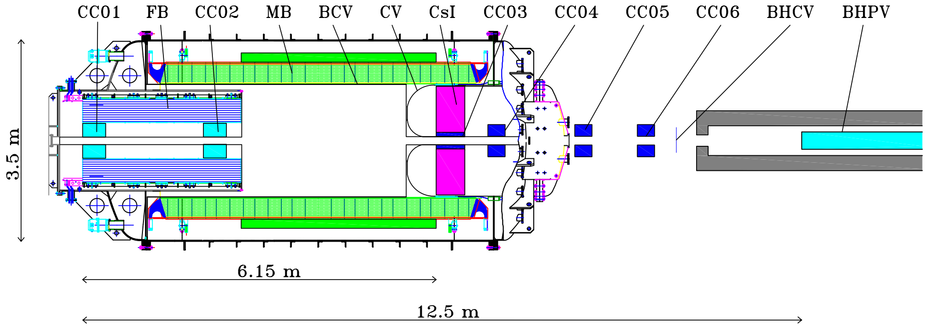

Fig. 4. – KOTO detector.

The current best limit is set by the KEK-PS E391a experiment at 6.7×10^{-8} at 90% CL [7] without any event candidate. The branching ratio of this decay mode is theoretically limited to be smaller than 1.46×10^{-9} at 90% CL; this is called the Grossman-Nir bound [8]. This indirect limit is imposed from a measured branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ (1.73×10^{-10}, obtained by BNL E797/E949 experiments [9]) assuming the isospin symmetry.

The primary goal of the experiment is to reach the limit predicted by the SM below the Grossman-Nir bound using a detector system, shown in fig. 4, integrated by upgrading the previous E391a detector. A new CsI calorimeter will be constructed by assembling crystals obtained from the KTeV experiment. All detector signals are recorded using waveform digitizers in order to improve the event reconstruction reliability and background rejection capability.

A neutral kaon beam line has been newly constructed in the particle and nuclear physics experimental hall. At the beginning of 2010, a beam survey was conducted utilizing a neutral kaon decay mode, $K_L \to \pi^+\pi^-\pi^0$ (13%), produced by a 1 kW slow-extraction beam. A clear peak corresponding to K_L was successfully recognized in a mass spectrum with two sets of hodoscopes and two arrays of pure-CsI crystal calorimeters.

In 2010, KOTO plans to complete the construction of the CsI calorimeter. An engineering run is scheduled to study K_L beam properties using the calorimeter. In 2011, it is expected that the detector will be installed, following which a full engineering run will be carried out. Data acquisition (physics run) is expected to start after this with 10% of the proposed beam intensity for one month. It is expected that KOTO will reach the Grossman-Nir limit with these statistics.

3. – Muon programs

The search for lepton-flavor violation (LFV) processes using muons is considered to play an important role in revealing a new physics beyond the SM thanks to the unique features of muons. Extremely precise measurements of well-known muon properties can also address possible new physics effects in comparison with those expected from the SM. At J-PARC, two μ-e conversion search experiments and one precision measurement of muon g-2 and EDM are planned to be conducted by utilizing the superior characteristics of the primary proton beam.

3·1. *COMET*. – The COherent Muon-to-Electron Transition (COMET) experiment is planned to be launched in the particle and nuclear experimental hall [10]. COMET

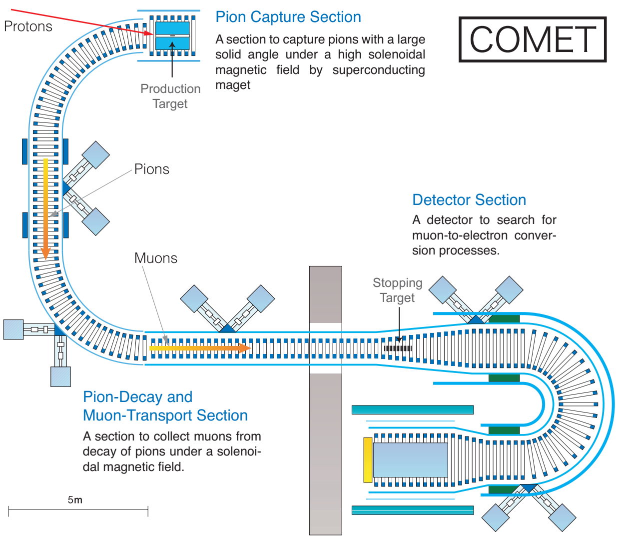

Fig. 5. – Setup of the COMET experiment.

aims to achieve a sensitivity of 10^{-16} to detect an LFV muon-to-electron transition (μ-e conversion) using an aluminum target. Because LFV processes are strictly forbidden in the framework of the SM, the discovery of the μ-e conversion will serve as remarkable evidence of a new physics beyond the SM. Many theoretical models incorporating the insufficiency of the SM predict the existence of the μ-e conversion immediately below the current experimental bound of 7×10^{-13} set by the SINDRUM II experiment [11].

The proton beam used for the COMET experiment is extracted from the MR at 8 GeV in order to suppress anti-proton production that may possibly cause an unwanted background in the experiment. Extraction is carried out by employing the bunched-slow extraction method, as already explained. The extracted beam is transported to a pion production target surrounded by a super-conducting solenoid magnet to collect and transport pions toward the transport solenoid magnet. Most pions decay to muons (and neutrinos) during these capture and transport processes, and these muons are transported through a curved transport solenoid to be stopped at the muon stopping target. The COMET detector located in a larger solenoid magnet is connected to the stopping target with another curved solenoid. A schematic view of the experimental setup is shown in fig. 5.

The signal of the μ-e conversion will be an electron emission with a characteristic energy (105 MeV) as large as the muon mass from muonic atoms. Muons in muonic atoms have a lifetime of 880 ns when aluminum is used as a muon-stopping target. In order to maximize the sensitivity of the experiment, two curved solenoids are used for transporting muons and electrons with large momentum and spacial acceptance. Because the centers of the helical trajectories of charged particle drift vertically as particles travel through curved solenoids depending on their momentum (and charge), a compensating vertical field is applied winding superconducting wires with a small tilt. This feature of the curved solenoid enables us to select the momentum of particles by locating collimators at suitable locations. In the muon transport curved solenoid, high-momentum muons above 75 MeV/c are stopped by a collimator, and in the detector curved solenoid, electrons below 60 MeV/c are stopped and 60–100 MeV/c electrons are reduced before entering the detector.

In this experiment, the pulse structure of the proton beam is very important because the primary proton beam hitting the pion production target produces a large background with prompt timing. To suppress this, the experiment opens the data acquisition window 600 ns after the primary proton pulse hits the production target. Thus, if any proton arrives at the target off-timing, that can easily produce a background that can possibly be misidentified as a μ-e conversion signal.

Currently, the COMET Collaboration is studying the time structure of the J-PARC proton beam and also conducting R&D on the detector components in order to start physics data acquisition some time around 2016–2017 followed by an engineering run.

3˙2. *DeeMe.* – COMET is considered to have a real chance of discovery if it can realize its target sensitivity; however, the construction necessary to start the experiment can take as long as 5–6 years because of the technical and financial requirements. Therefore, another μ-e conversion search experiment has been considered to study the physics with less sensitivity but with the earlier realization. DeeMe plans to attain a μ-e conversion search sensitivity of 10^{-13}–10^{-14} by using carbon or aluminum as a target. The proton beam at the MLF will be used in this experiment. DeeMe does not transport the muon beam as COMET does but tries to measure only the delayed electrons emitted directly from a pion production target (carbon) or from a muon stopping target (aluminum) that will be located very close to the pion production target. A muon beam line in the MLF facility is used as an electron spectrometer. The feasibility of this experiment is being carefully checked by conducting tests at the beam line.

3˙3. *Muon g-2/EDM measurement.* – An experimental proposal has been submitted to measure the muon g-2 and electric dipole moment by using the J-PARC MLF muon beam [12]. In this experiment, the muon beam is generated by accelerating muons produced from muoniums. Those muoniums are formed by stopping the surface muon beam in a material and then shooting a powerful pulsed laser at a suitable timing to remove electrons. Thus, a muon source with very small momentum dispersion, which is actually almost at rest, is obtained. Then, the muons are accelerated by a muon linac to $300\,\mathrm{MeV}/c$ for the experiment. Thanks to this innovative method to generate a muon beam with very small momentum spread in a transverse direction, the experiment can conduct a g-2 measurement using a completely different configuration from the previous measurement performed at BNL [13]. This also enables the measurement of the muon EDM with the same setup because no electric field is required to focus the beam. The collaboration is carring out R&D on components required to realize such an unprecedented muon beam with an intensity of 10^6 muons/s and to start the experiment in a few years.

4. – Conclusions

J-PARC has recently commenced operations and its power is currently being upgraded. As described in this presentation, interesting kaon and muon programs are planned to be conducted using the high-performance beam available at J-PARC. Fruitful particle physics results are expected as the machine demonstrates a step-by-step achievement of its primary performance.

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