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The Reopening of the Research Activities of the Hypernuclear and Hadron Physics at the J-PARC Hadron Hall

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Recovery of the J-PARC Hadron Experimental Facility from the radioactive material leakage incident occurred on May 23, 2013 is reported. After long-term efforts for renovation of the facility, we completed it at the end of March 2015 and then restarted the beam operation of the facility on April 9, 2015. Experiments with slow extraction beams started on April 24, 2015. The beam intensity delivered to the Hadron Experimental Facility reached approximately 42 kW by the end of 2015, which is almost twice higher than the beam power before the incident. Recent new activities especially on strangeness nuclear physics in the Hadron Experimental Facility are also summarized briefly in this report.

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1. Introduction to J-PARC

J-PARC (Japan Proton Accelerator Research Complex) is the most advanced brand-new accelerator facility in Japan [1][2]. It consists of three accelerators, 400 MeV Linear Accelerator (LINAC), 3 GeV Rapid Cycle Synchrotron (RCS) and 50 GeV Main Ring (MR, now operated at 30 GeV). The most important characteristic of J-PARC is its high design beam power, 1 MW for both RCS and MR. RCS provides intense proton beams to the neutron spallation source (n) and the pulsed muon source (μ) prepared in Materials and Life Science Facility (MLF). Some fraction of the beam extracted from RCS is injected to MR and accelerated up to 30 GeV. MR has two extractions, one for the fast extraction to the Neutrino Beam Facility (ν) for a long baseline neutrino oscillation experiment, T2K, and the other for the slow extraction to the Hadron Experimental Facility (Hd) [3][4] for various fixed-target counter experiments. The four experimental facilities (n, μ, ν, and Hd) provide their characteristic beams for experimental users. Even after the big earthquake occurred on March 11, 2011, we resumed user beam operation after the 10 months beam-off period for recovery.

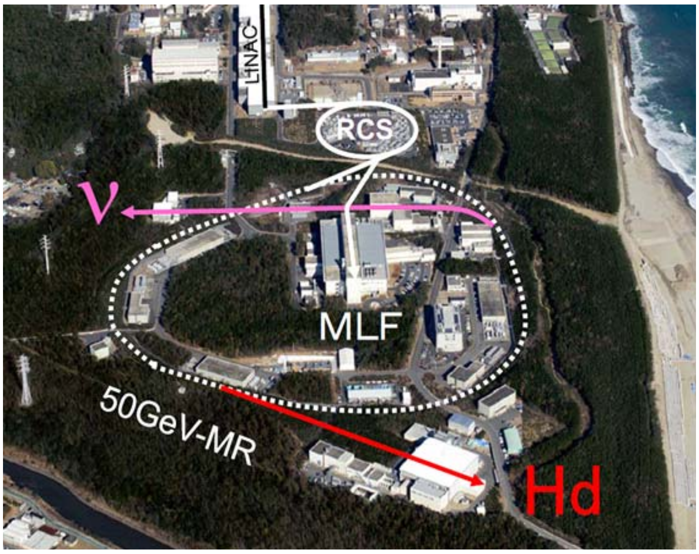

Figure 1. *J-PARC site at Tokai campus of JAEA. "Hd" means the Hadron Experimental Facility for fixed target experiments with slow extraction. "ν" indicates the Neutrino Beam Facility with fast extraction. "MLF" indicates the Material and Life Science Facility where the spallation neutron (n) and pulsed muon (μ) sources are operated by using intense 3 GeV proton beam provided by Rapid Cycle Synchrotron (RCS).*

Unfortunately, we had another incident on May 23, 2013, leakage of radioactive materials at the Hd [5]. After the incident, J-PARC experienced a long shut down again in order to improve its safety performance. As results of the improvements, MLF resumed its operation in February 2014, and ν restarted its neutrino aiming to SuperKAMIOKANDE in May 2014. However the renovation programs for Hd took a much longer time, but they were completed by the end of March 2015.

On April 9, 2015 at 23:11 pm (JST), we had the first slow extraction beam from MR to Hd after the radiation leak incident. It was almost two years after the incident of Hd. Immediately after the first beam, we made a lot of safety performance tests for various components related to the beam handling in Hd, i.e. interlocks, human interfaces including various displays, and many other things. Tuning of the slow extraction itself was, of course, intensively done! Inspection by the radiation safety authority was made on April 17 under the actual beam extraction condition, and we received a new operation license of Hd on April 20. On April 24, we restarted the beam operation of Hd for experimental users.

2. Hadron Hall Incident

At present it has become clear that the radioactive material leakage incident, which occurred on May 23, 2013, proceeded through the following five stages.

1. Due to malfunction of the electromagnets which control the slow extraction of MR, a sharply-pulsed more than 100 times intense proton beam was transported to the secondary particle production target made of gold, which was placed in the Hadron Experimental hall (Hd-hall) of the Hadron Experimental Facility (Hd).
2. The gold target was instantaneously heated up to a high temperature and partially damaged, causing vaporization of gold and dispersion of radioactive material accumulated in the gold target itself.
3. The radioactive material leaked into the beam line tunnel which housed the primary proton beam line, because the target container was not very tightly hermetically-sealed.
4. The radioactive material leaked into the Hd-hall since the airtightness of the beam line tunnel was not perfect. At this point workers in the Hd-hall were exposed to radiation.
5. Due to operation of exhaust ventilation fans in the Hd-hall, the radioactive material was released to the environment outside of the radiation controlled area of the Hd-hall and J-PARC.

Thirty-four out of 102 people staying in the Hd-hall during the incident was internally exposed to radiation. The maximum amount of their radiation doses was found to reach 1.7 mSv through their life by means of a whole-body counter measurement. Fortunately medical examination confirmed the absence of any adverse effects due to the radiation exposure. The total amount of radioactive material released into the Hd-hall was estimated to be approximately 20 billion ($2\text{x}10^{10}$) Bq. The radiation dose on the site boundary at the location closest to the Hd-hall was estimated to be below 0.29 μSv.

Based on our analysis of this incident through the process described above, we established a recovery plan of Hd-hall against the recurrence of similar incidents. The frameworks for the recovery plan are as follows;

1. preventive measures against malfunction of electromagnets for slow extraction,
2. ensuring of airtightness of the target container and the beam line tunnel,
3. management of exhaust ventilation from Hd-hall,
4. reinforcement of monitoring radioactivity in and around the Hd-hall.

It is important to decrease frequency of malfunction of the MR magnet power supply system. However, we know that it is impossible to completely eliminate malfunction of accelerator system even through various preventive measures. The essentials of the preventive measures against radioactive material leakage are reinforcement of airtightness of the target container and the beam line tunnel. The exhaustion of the air from a stack through filters after checking concentration of radioactive material is also important. In this sense the frameworks 2~4 are essential for the Hd-hall renovation.

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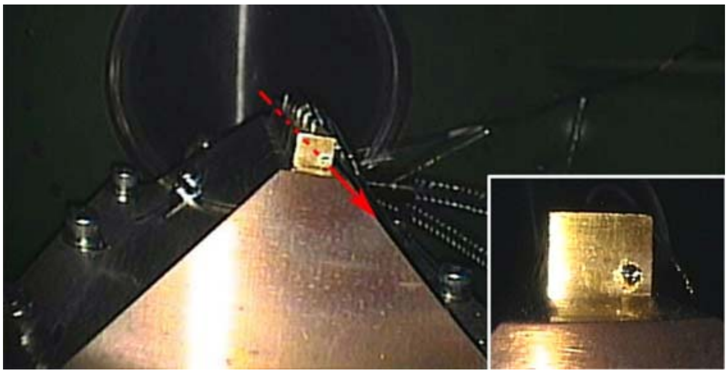

Figure 2. *Photograph of the damaged gold target observed from the downstream: a hole with a 1 mm diameter was found at the downstream end, as shown in the expanded view of the downstream surface of the target. Red arrow in the photograph shows the beam direction.*

In December 2013, we successfully observed the gold target at the Hd-hall using a fiberscope for the first time after the incident. Though the observation, we confirmed:

1. a hole of 1 mm in diameter at a downstream end of the gold target,
2. gold-colored nubs, which probably are traces of dripped-out melted gold through slits of a gold rod of the target,
3. probably droplets of melted gold on the copper base block and
4. traces of sprayed-out melted gold on a beryllium vacuum window placed at the downstream of the target.

These observed facts matched with our expectation and simulation results on the process of the incident. Consequently, we consider that at the beam injection the temperature of the gold target partially exceeded the melting and, furthermore, boiling points, and melted gold was pushed outward due to a rapid volume expansion resulted from vaporization of the melted gold.

3. Hadron Hall Renovation

As a new production target, we designed and manufactured an indirectly water cooled gold target with more efficient water cooling paths. The target can be used up to 50 kW with 2 s slow extraction time. The target was placed in a newly prepared hermetically-sealed target container filled with helium gas. Helium gas is circulated by a pump placed almost 50 m away from the target container. Radioactivity contained in the helium gas is monitored by a Ge detector placed near the pump. Thus we can detect target failure by measuring unexpected amount of radioactive fragments produced from gold nuclei in the target. The temperature of the target is always monitored by thermocouples with a measurement frequency increased to every 100 ms. Then heating up and cooling down trends of the target temperature can be recorded in detail and compared with the calculated ones via FEM analysis.

The beam line tunnel for the primary proton beam is air-tightly sealed with double layers of air-tight film, which is usually used for manufacturing of balloons. Leakage through the double seal layers measured by a helium leak detector was found to be sufficiently small. Two types of new exhaust air ventilation system were introduced to the Hd-hall. One has an air exhaust volume of 10000 m^3/h, and the other has 74000 m^3/h. Both systems can exhaust the air inside the Hd-hall through filters. The 10000 m^3/h air exhaust system is sufficient for usual radiation control inside the Hd-hall. However, 74000 m^3/h air exhaust system is necessary for keeping clean circumstance in the Hd-hall. This large-scale 74000 m^3/h system can exchange the whole air inside the Hd-hall with flesh air within one hour in case of need.

The interlock system on radiation related matters of the Hadron Experimental Facility (Hd) was completely renewed and strengthened. The fast target temperature monitor and the target gas radiation monitor described above are typical examples. In addition, the system for sharing safety information was greatly strengthened. Experimental team members inside the Hd-hall are automatically included in the beam operation team and can share the radiation interlock signals. The team members have to take a set of safety training classes before the beam usage. The emergency drills were conducted together with the users assuming several abnormal and/or serious situations. After these renovations in both software and hardware sides, we successfully restarted the beam operation of the Hd.

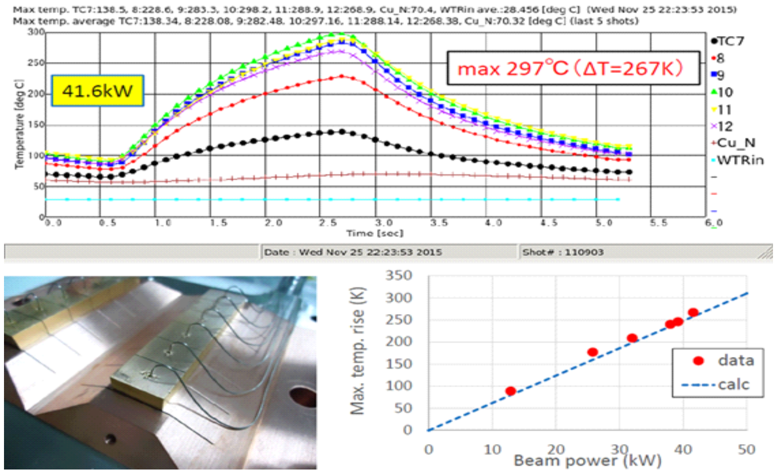

Figure 3. *Temperature change of the new gold target measured every 100 ms (top). The target was divided into 6 segments as shown in the bottom-left photo. The temperature of each segment was measured independently. Measured data agreed well with calculated results obtained from FEM analysis (bottom-right).*

Now in the middle of 2016, in the Hd-hall, two charged particle beam lines (K1.8 and K1.8BR) and one neutral kaon beam line (KL) are available for physics experiments. These three beam lines are connected to the only one production target, T1, placed at the upstream part of the Hd-hall. K1.8 provides kaons up to 2 GeV/c with excellent kaon purity mostly used for hypernuclear experiments. For this purpose K1.8 employs double-stage electrostatic beam separation. K1.8BR is the beam line branched from the middle of K1.8 and provides kaons up to 1.2 GeV/c. K1.8 and K1.8BR cannot be operated at the same time. KL beam line is used to search for the rare kaon decay process of $K^{0}_{L} \rightarrow \pi^{0}\nu\nu^{bar}$. Two new charged particle beam lines (K1.1 and π1) will be constructed and connected to the T1 target. K1.1 is the low momentum (up to 1.1 GeV/c) kaon beam line with double-stage electrostatic separation. π1 is the unseparated beam line up to 1 GeV/c for test experiments.

A set of new primary proton beam lines are under construction in Hd. The High-p beam line is branched from the original primary proton beam line, A line, at the middle of A line, and it is called "B line". At the High-p beam experimental area, experiments using 30 GeV primary protons can be performed. A large-size spectrometer magnet has already been placed there. The High-p beam line can be also used as a high momentum unseparated secondary particle beam line up to 20 GeV/c by placing a production target at the branching point from A line. The

COMET beam line is the branched beam line from the High-p line, and it is called "C line". Slow-extracted primary proton beams up to 8 GeV will be introduced to the COMET experimental area for the μ-e conversion experiment. This COMET experimental area is prepared in the newly constructed South Annex of the Hd-hall in connection with the beam operation headquarters.

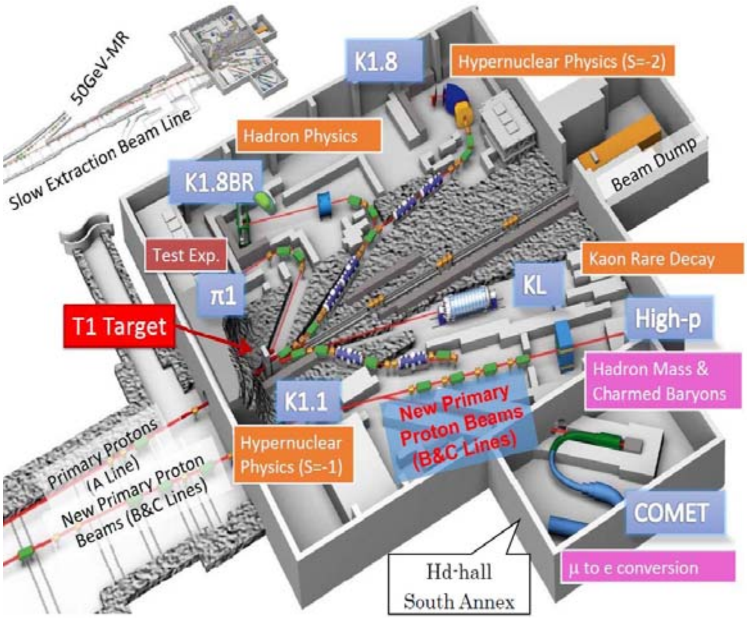

Figure 4. *Beam line status of the Hd-hall. K1.8, K1.8BR and KL beam lines are active and physics experiments are running. High-p, COMET and the downstream part of K1.1 are now under construction and modification. The test beam line π1 will be also constructed.*

4. Physics Results from Hadron Hall

In 2015 and 2016, exciting new data have been obtained with the beam time resumed after the renovation. The E13 group lead by Tohoku University developed a new type of Ge detector array dedicated to hypernuclear γ-ray spectroscopy, named "Hyperball-J", and successfully measured γ-rays from ${}^{4}_{\Lambda}$He hypernuclei produced via the ^{4}He(K^{-}, π^{-})${}^{4}_{\Lambda}$He reaction. The observed γ-ray from the first excited 1^{+} state to the ground 0^{+} states, corresponding to the spin-flip M1 transition of Λ hyperon in the ^{3}He core, was found to have an energy of 1.406 MeV. Surprisingly, it is much larger than the known γ-ray energy of 1.09 MeV for the $1^{+}\rightarrow 0^{+}$ transition of the mirror hypernucleus, ${}^{4}_{\Lambda}$H (the spin-flip M1 transition of Λ particle in ^{3}H core). The Λ–nucleon force is expected to be almost identical between Λ–p and Λ–n due to charge symmetry, and thus the Λ binding energies and the level structure of mirror Λ hypernuclei should be the same. The observed difference of the (1^{+},0^{+}) level spacing (0.32 MeV), much larger than the binding energy difference of ~70 keV between ^{3}H and ^{3}He with the electromagnetic effects removed, indicates that a hyperon breaks charge symmetry. This result will be used for a stringent test of theoretical models of the baryon-baryon interactions, namely, the generalized nuclear force including hyperons. Some theoretical model suggests the ΛN-ΣN coupling force is responsible for the observed large effect of charge symmetry breaking. Details are described in Reference [6].

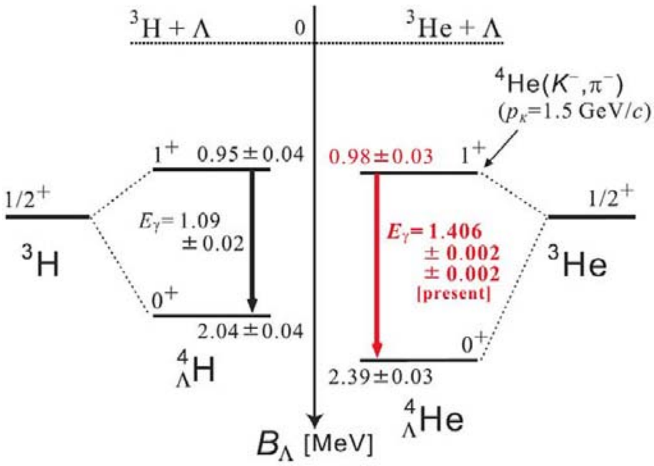

Figure 5. *Level schemes of the mirror hypernuclei, $^4_\Lambda$H and $^4_\Lambda$He, indicating a large charge symmetry breaking (CSB) effect. The γ-ray for $^4_\Lambda$He($1^+ \to 0^+$) was measured in the beam time just after the renovation of Hadron Experimental Facility, i.e. in April 2015. Comparing with the corresponding γ-ray for the mirror hypernuclei, $^4_\Lambda$H($1^+ \to 0^+$), the (1^+,0^+) energy spacing is found to be different by more than 0.3 MeV between $^4_\Lambda$H and $^4_\Lambda$He.*

Another important step made in the resumed Hd-hall was the search for the K^-pp (deeply-)bound state. The E15 experiment has measured a missing mass spectrum for the ^{3}He(K^-,n) reaction and invariant mass spectra for decay particles from the produced K^--nuclear system. The Λp invariant mass spectrum exhibited a significant number of events below the K^-pp threshold [7]. New high-statistics data collected in 2015 will provide decisive results for this exciting topic.

Along with the increase of the accelerator beam power, double strangeness nuclear systems have become one of the most important and unique subjects at the J-PARC Hadron Experimental Facility. The E05 group lead by Kyoto University carried out a pilot run for the Ξ^--hypernuclear spectroscopy experiment via the ^{12}C(K^-,K^+) reaction, using the existing SKS spectrometer [8] and successfully obtained a missing mass spectrum which would indicate existence of Ξ^- hypernuclear bound states. The main data-taking will be done after the newly-built magnetic spectrometer, S-2S, is installed at the K1.8 beam line. In addition, another experiment on double strangeness systems (E07) has started data-taking in 2016; it aims at collecting one hundred samples of ΛΛ hypernuclei in nuclear emulsion where Ξ^- hyperons produced by the (K^-,K^+) reaction are injected. It also measures Ξ^--atomic X-rays with Ge detectors.

5.Hadron Hall Extension

Even after restarting of the operation of the Hadron Experimental Facility (Hd), demand for more beam time and request for new types of secondary beams have been increasing. To answer the requests, we are now trying to extend the Hd-hall three times in area as shown in Figure 6. Two new target stations will be constructed and four new secondary beam lines will be connected to these two targets. The neutral kaon beam line at a very forward angle (KL), the high momentum (up to ~10 GeV/c) separated kaon/antiproton beam line (K10), the high resolution dispersion matching beam line (HIHR) and the low energy separated kaon beam line (K1.1, to be moved from the present Hd-hall) are now under consideration. Once the extension is completed, the Hd of J-PARC will be a real Mecca of nuclear and particle physics using kaons and other rare hadronic beams.

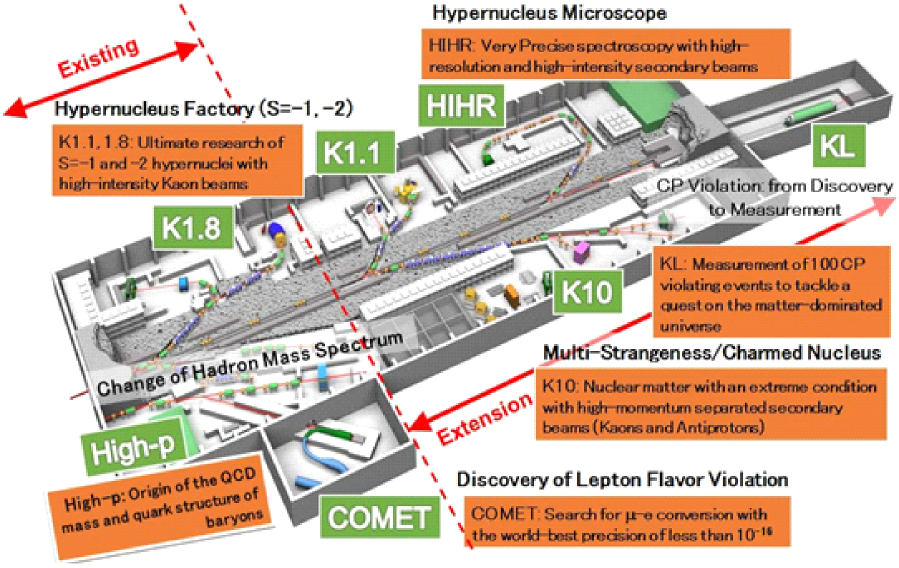

Figure 6. *Layout for the Hd-hall extension. Two new target stations are constructed and four new secondary beam lines are connected to these two targets. The neutral kaon beam line at a very forward angle (KL), the high momentum separated kaon/antiproton beam line (K10), the high resolution dispersion matching beam line (HIHR), and the low energy separated kaon beam line (K1.1) are now under consideration.*

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