Plans for Hadronic Structure Studies at J-PARC

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Abstract. Hadron-physics projects at J-PARC are explained. The J-PARC is the most-intense hadron-beam facility in the multi-GeV high-energy region. By using secondary beams of kaons, pions, and others as well as the primary-beam proton, various hadron projects are planned. First, some of approved experiments are introduced on strangeness hadron physics and hadron-mass modifications in nuclear medium. Second, future possibilities are discussed on hadron-structure physics, including structure functions of hadrons, spin physics, and high-energy hadron reactions in nuclear medium. The second part is discussed in more details because this is an article in the hadron-structure session.

1. Introduction
The J-PARC stands for Japan Proton Accelerator Research Complex [1], which is located at Tokai in Japan. It is a multi-purpose facility ranging from life sciences to nuclear and particle physics [2, 3]. The J-PARC accelerator consists of a linac as an injector, a 3-GeV rapid cycling synchrotron, and a 50 GeV synchrotron as shown in Fig. 1. The J-PARC has three major projects: (1) material and life sciences with neutrons and muons produced by the 3-GeV proton beam, (2) nuclear and particle physics with secondary beams as well as the primary-proton beam, (3) nuclear transmutation by the linac. The advantage of the facility is the beam intensity: 1 MW in the 3-GeV synchrotron and 0.75 MW in the 50 GeV one. At this beginning stage, the proton is accelerated to 30 GeV instead of the original 50 GeV, and the beam intensity has not reached to the designed level.

Hadron experiments are planned in the hadron experimental facility in Figs. 1 and 2. Various secondary beams such as pions, kaons, and anti-proton as well as the primary-proton beam are used for hadron-physics experiments [1, 2, 3]. The K1.8 and K1.1 beamlines are mainly for kaon beams with the momentum around 1.8 GeV/c and 1.1 GeV/c, respectively. The KL beamline is for measurements of neutral kaon decays, and the high-momentum beamline is for the primary proton beam. Currently, the K1.8, K1.8BR, KL, and K1.1BR beamlines are ready, the K1.1 will be ready in the near future, and the high-momentum beamline needs to be constructed.

In this article, the “hadron physics” is used by including nuclear projects in addition to hadron projects in a narrow sense. The hadron physics could also include neutrino interactions with nuclei in the T2K neutrino-oscillation experiment. However, this topic is not discussed in this article. The interested reader is referred to the proceedings of a dedicated international workshop [4]. The hadron-physics experiments at the hadron hall start from strangeness hadron physics such as hypernuclear physics and a test of pentaquark existence. Then, nuclear medium effects on hadron masses will be investigated. There are proposals on dimuon production ($J/\psi$, $Y$, and $\chi_c$) at the high-momentum beamline and on hyperon physics at the K1.1 beamline. The high-momentum beamline needs to be constructed in the near future.
Drell-Yan); however, they are not approved at this stage. In this article, we first explain some of the approved projects in Sec. 2, and then possible hadron-structure projects are introduced in Sec. 3. Here, we focus on hadron-structure projects because this article is in the hadron-structure session. These hadron-physics studies at J-PARC are summarized in Sec. 4.

2. Approved projects

All the J-PARC proposals on hadron physics are listed in Ref. [5]. Among them, some of approved experiments are explained first in this section. We list major purposes of these projects:

1. creation of new forms of hadronic systems by extending flavor degrees of freedom,
2. studies of hyperon interactions and their applications to neutron stars,
3. search of exotic hadrons including strangeness,
4. investigations on hadron-mass generation mechanism.

These projects should open a new realm of hadron physics.

2.1. Hypernuclear physics

In the beginning stage, one of the major projects is the hypernuclear physics [2]. It is intended to find new forms of hadronic many-body systems by extending flavor degrees of freedom as shown in Fig. 3, where the strangeness is taken as the third axis. The strangeness hadron physics is interesting with the following reasons. First, the strange-quark mass is the order of the QCD scale parameter $\Lambda_{QCD}$, which suggests that the strangeness is an appropriate quantity to probe QCD dynamics. Second, there is no Pauli blocking for hyperons ($Y$) in a nucleus, so that they are good probes of deep regions of nuclei. Third, hyperons could exist in neutron stars, so that information on $YN$ and $YY$ interactions should be important for understanding their properties [7].

As shown in Fig. 3, there are some data for hypernuclei with $S = -1$ but there are only a few data in the double strangeness plane. It is one of the major purposes of the J-PARC projects to find many new hypernuclei especially with $S = -2$. Then, $YY$ and $YN$ interactions should be clarified from their properties. Independent and direct measurements of $YN$ interactions are also considered, but there is no actual proposal at this stage. These interactions have renewed
interests because of recent developments in the field of lattice QCD for nuclear force and light nuclei [8].

2.2. Exotic hadrons
Exotic hadrons indicate hadrons with internal configuration other than ordinary $qq\bar{q}$ and $qqq$ types. This topic has been investigated for a long time since the early stage of quark models; however, an undoubted experimental evidence has not been found yet. Nonetheless, there are recent discoveries of their candidates in charmed hadrons particularly from the Belle and BaBar collaborations. In this section, kaonic nuclei are included as one of such projects. It seems that time has come to establish the field of exotic hadrons with experimental confirmations. In Japan, an exotic-hadron project started in 2009 by forming groups of many experimentalists and theorists [9] for searching exotics at KEKB, SPring8, and J-PARC, and its activities are in progress.

The first experiment at the K1.8 beamline is a test of $\Theta^+$ existence by the $\pi^-p \rightarrow K^-\Theta^+$ reaction as shown in Fig. 4. A possible pentaquark state $\Theta^+$ has been controversial for several years due to many negative experiments. On the other hand, there are still positive measurements. For example, a recent report from the LEPS collaboration repeatedly indicated its existence [10]. It is important to do a decisive measurement at J-PARC. $S$-channel formation by $K^+ + d$ could be such an experiment [11]. However, the reaction $\pi^-p \rightarrow K^-\Theta^+$ will be investigated first because the kaon-beam intensity is still low in the beginning operation of the J-PARC.

Few-body bound states of kaon and nucleons are also interesting since there are experimental reports on their candidates. This topic originates from an indication that $\Lambda(1405)$ is a bound state of $\bar{K}N$. Then, an attractive $\bar{K}N$ interaction could make it possible to form bound states $\bar{K}NN$, $\bar{K}NNN$, and so on [12], which are called kaonic nuclei. Recent research activities are focused on simple systems $\Lambda(1405)$ and $K^-pp$ among them. The first experiments at the K1.8BR beamline are on the $K^-pp$ bound state and $\bar{K}N$ interactions as shown in Figs. 5 and 6, respectively. The $K^-pp$ bound state is searched in two ways by missing-mass spectroscopy with the measurement of a neutron and by invariant-mass reconstruction with the measurement of decay particles. In the E17 experiment in Fig. 6, the $X$-ray is observed for the $3d \rightarrow 2p$ transition of the kaonic helium-3. The $2p$ energy level is sensitive to the strong interaction of $\bar{K}N$, and its effect should be reflected in the $X$-ray energy. Therefore, this experiment provides us valuable information for finding the controversial strength of $\bar{K}N$ interactions. There are also experiments for investigating the nature of $\Lambda(1405)$ [15].

![Figure 4. Test of $\Theta^+$ existence.](image4.png)

![Figure 5. Search for $K^-pp$ bound state [13].](image5.png)

![Figure 6. X ray from kaonic helium-3 [14].](image6.png)
2.3. Hadron masses in nuclear medium

The origin of hadron masses will be investigated by using the primary-proton beamline by observing light vector-meson masses in nuclear medium. We know that up- and down-quark masses are much smaller than the nucleon mass, which makes us wonder how the major part of the nucleon mass, or generally hadron masses, is generated. A possible idea is due to chiral symmetry breaking. An order parameter of the breaking is the quark condensate $<q\bar{q}>$. However, it is not an observable, so that meson-mass shifts, which are connected to the condensate, are investigated experimentally in nuclear medium [16].

This topic has been investigated in various facilities including the KES-PS with the primary 12-GeV proton beam: $p + A \rightarrow V + X$ ($V = \rho, \omega, \phi \rightarrow e^+e^-$) [17] as shown in Fig. 7. They observed 9% and 3% mass shifts for $\omega (\rho)$ and $\phi$, respectively. These measurements will be continued at J-PARC with much better statistics.

3. Possibilities of hadron structure studies

Since this article is in the hadron-structure session, it is appropriate to focus on hadron-structure projects at J-PARC. Some ideas are introduced in this section; however, the reader should be aware that the following topics have not yet been officially approved or even that a proposal does not exist for some projects. It inevitably means that discussed topics are somewhat based on author’s personal view. New ideas are welcome as the forms of experimental proposals and/or contributions to J-PARC workshops [18]. All the following projects, as well as the above meson-mass measurements, use the high-momentum primary-proton beamline as indicated “High p” in Fig. 2. This beamline needs to be constructed in the near future. We list major purposes of the hadron-structure projects:

(1) investigations on applicability of perturbative QCD,
(2) search for origin of nucleon spin,
(3) establishment of parton distribution functions at large $x$,
(4) investigations on mechanisms of quark and hadron interactions in nuclear medium.

These studies lead to the establishment of hadron and nuclear structure at large $x$ as a complimentary project to RHIC and LHC. They also provide basic information on proton structure for new discoveries such as at LHC.

3.1. Applicability of perturbative QCD

The proton-beam energy of 50 GeV (currently 30 GeV) corresponds to the c.m. energy $\sqrt{s} = 10$ GeV, which is rather low in comparison with the RHIC and LHC energies. It suggests that perturbative QCD (pQCD) corrections should be large. In order to extract meaningful results on parton structure, one needs to remove perturbative effects from measured data. Therefore, it is essential to understand the pQCD corrections at the J-PARC energy.

In the last several years, theoretical techniques, especially on gluon resummations, have been developed for describing fixed-target cross sections. It is now known that the large corrections mainly come from threshold gluon emissions ($m_{\mu \mu}^2 \sim \bar{s}_{q\bar{q}}$ in Drell-Yan processes with dimuon mass $m_{\mu \mu}$ and c.m. energy squared $s_{q\bar{q}}$ for $q\bar{q}$). Such corrections are estimated for the Drell-Yan processes at the J-PARC energy [19], and the results indicate that the resummation effects are indeed large. However, NLL (next-to-leading logarithmic) and NNLL (next-to-next-to-leading logarithmic) cross sections are similar, which indicates that the resummation series are converging in the Drell-Yan if the NNLL resummations are taken at $\sqrt{s} = 10$ GeV.
The J-PARC energy is the transition region from hadron degrees of freedom (d.o.f.) to quark-gluon d.o.f., and it is a boundary in applying perturbative QCD. For the Drell-Yan at $\sqrt{s} = 10$ GeV, the pQCD corrections can be understood by including the gluon resummations, so that parton-structure information should be extracted from the data. On the other hand, this energy region is challenging and attractive for pQCD theorists in testing their calculations. Such basic studies are essential for establishing hadron physics from a description in terms of hadrons to the one in terms of quarks and gluons.

3.2. Flavor dependence of antiquark distributions

There are proposals on dimuon experiments by using the primary proton beam [20, 21]. The J/ψ production and Drell-Yan measurements are intended to investigate structure functions at medium Bjorken variable $x$. The E906/SeaQuest experiment at Fermilab is in progress for dimuon experiments, and it could be continued at J-PARC. For example, the Drell-Yan cross sections are measured for $pp$ and $pd$ ($p$: proton, $d$: deuteron), and then their ratio is taken for finding the flavor dependence of antiquark distributions: $\frac{\sigma_{DY}^{pd}}{2\sigma_{DY}^{pp}} \approx (1 + \bar{d}/\bar{u})/2$ as shown in Fig. 8. The Fermilab-E866 experiment provided a clear evidence for the flavor-asymmetric antiquark distributions $\bar{u} \neq \bar{d}$. The E906/SeaQuest and J-PARC measurements are expected to extend the $x$ range to a larger-$x$ region. In particular, the measured E866 ratios tend to decrease as $x$ becomes larger in Fig. 8, which is difficult to be interpreted theoretically. The flavor asymmetric antiquark distributions cannot be explained by a perturbative QCD mechanism because up- and down-quark masses are very small, so that it is mainly associated with nonperturbative properties such as pion clouds in the nucleon [22].

Measurements of antiquark distributions in nuclei are also interesting. The Fermilab Drell-Yan measurements showed that nuclear modifications of the antiquark distributions are very small at $x \sim 0.1$, which ruled out the pion-excess mechanism. Since the past Fermilab measurements are limited to a narrow kinematical region at $x \sim 0.1$, it is desirable to extend them to larger $x$ by J-PARC experiments. Determination of nuclear parton distribution functions (PDFs) at large $x$ is valuable for understanding the nuclear modification mechanism and in general for precisely calculating other high-energy reactions, for example, high-$p_T$ jet and hadron production cross sections at LHC.

3.3. Spin physics without proton-beam polarization

The nucleon spin is one of fundamental physics quantities, yet its origin is not known in terms of quark and gluon degrees of freedom. In a simple quark model, it is supposed to be explained by a three-quark-spin combination as shown in the left part of Fig. 9, which is denied by polarized lepton-nucleon scattering experiments [24]. The gluon polarization seems to be also small according to recent lepton-scattering and RHIC-Spin measurements, so that the remaining possibility is a significant contribution from orbital angular momenta as illustrated in Fig. 9. The J-PARC facility could contribute various aspects of such high-energy spin studies. Since the current proton-beam energy is 30
GeV without polarization, initial spin-physics projects should be carefully planned with target polarizations and new observables, which are not (well) investigated at the Brookhaven AGS.

### 3.3.1. Transverse-momentum-dependent distributions

Nucleon structure has been investigated in a collinear factorization form by integrating transverse momenta; however, it is now becoming possible to investigate more details on transverse structure. Such studies are valuable for clarifying the nucleon spin issue, particularly on the orbital-angular-momentum part, and in general for describing high-energy hadron reactions at RHIC and LHC.

Aforementioned Drell-Yan measurements can be used for investigating a transverse-momentum-dependent (TMD) polarized parton distributions, so called Boer-Mulders (BM) functions, by observing violation of the Lam-Tung relation in the Drell-Yan cross sections [21]. The BM functions indicate transversely-polarized quark distributions in the unpolarized nucleon. Other interesting TMD distributions are the Sivers functions, which indicate unpolarized quark distributions in the transversely-polarized nucleon. For example, they appear in single spin asymmetries of hadron-production processes \( p + \bar{p} \rightarrow h + X \). These distributions are spin-dependent TMD distributions, namely correlations between the transverse momentum and spin, so that they should be related to angular momentum effects in the nucleon. Their measurements are valuable for understanding transverse-spin structure and for testing an interesting relation to semi-inclusive lepton measurement in the sense the TMD distributions change sign due to gauge-link properties in these processes [21]. An advantage of J-PARC measurements is, for example, illustrated in Fig. 10, where single spin asymmetries of \( D \)-meson production at J-PARC and RHIC are shown by considering the Sivers' mechanism [25]. It is obvious that quark Sivers functions are determined well at J-PARC, whereas measurements are sensitive to gluon Sivers functions at RHIC. Therefore, the J-PARC experiment is complementary to the RHIC one.

### 3.3.2. Applicability of perturbative QCD to elastic single-spin asymmetry

Perturbative QCD has been established for many high-energy processes. However, its applicability to elastic spin asymmetries is not understood in the sense, for example, that the single-spin asymmetry in \( pp \) tends to increase as \( p_{\perp} \) becomes larger according to AGS measurements [26], whereas it should vanish in perturbative QCD. As shown in Fig. 11, the AGS measurements are up to \( p_{\perp}^2 = 8 \text{ GeV}^2 \), where some nonperturbative mechanism would still contribute to the finite asymmetry. In any case, the AGS measurements need to be confirmed by an independent experiment because it is difficult to find a possible mechanism to explain it. However, the current 30-GeV beam energy is similar to the AGS one, so that other observables need to be considered in addition to a mere confirmation, for example, by changing targets and/or by considering angular distributions in order to provide clues for theorists to understand the mechanism for the finite asymmetry.

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**Figure 10.** Single spin asymmetry in \( D \)-meson production at J-PARC and RHIC [21, 25].

**Figure 11.** Elastic single spin asymmetry in \( pp \) [26].
3.3.3. Generalized parton distributions at hadron facilities

Generalized parton distributions (GPDs) are global quantities in describing the nucleon because their forward limits are form factors, first moments are the PDFs, and second moments are related to orbital angular momentum contributions to the nucleon spin. In Fig. 12, the GPD integrated over the transverse-momentum transfer $H(x, \xi = 0, -\Delta^2_{\perp})$ is shown for illustrating that the GPDs are related to the 3-dimensional picture of the nucleon.

The GPDs have been studied mainly in the virtual Compton process in deep inelastic lepton scattering. However, the GPD studies could be done at hadron facilities by using exclusive hadron-production reactions $a+b \rightarrow c+d+e$ such as $N+N \rightarrow N+\pi+B$, where $B$ is $N$ (nucleon) or $\Delta$ as shown in Fig. 13 [28]. Here, hadrons $c$ and $d$ have large and nearly opposite transverse momenta and a large invariant energy, so that an intermediate exchange could be considered as a $q\bar{q}$ state. The $q\bar{q}$ attached to the nucleon or $N \rightarrow \Delta$ is expressed by the GPDs in a special kinematical region, so called Efremov-Radyushkin-Brodsky-Lepage (ERBL) region ($-\xi < x < \xi$), which is in the middle of three regions of Fig. 14. The hadron measurements of the GPDs are complementary to lepton-facility experiments in the sense that the specific kinematical region (ERBL) is probed by extending the region of $x$ to medium $x$ because of the J-PARC beam energy (30-50 GeV) and large cross sections of strong interactions.

![Figure 12. 3-dimensional picture of nucleon by GPDs [27].](image1)

Figure 13. GPD studies at hadron facilities [28].

3.3.4. Tensor structure in terms of quark and gluon degrees of freedom

Tensor structure often appears in nuclear physics. For example, the $D$-state admixture in the deuteron is the origin for the finite electric quadrupole moment of the deuteron. It is interesting to describe the tensor structure in terms of quark and gluon degrees of freedom. Deep inelastic charged-lepton scattering from a tensor-polarized deuteron was investigated by the HERMES collaboration, and tensor polarized PDFs are extracted from their data [29]. It is particularly interesting to find a finite tensor-polarized antiquark distribution $\delta_T\bar{q}(x)$, which comes from the violation of the sum rule $\int dx b_1(x) = 0$ [29] as shown in Fig. 15. This finite $\delta_T\bar{q}(x)$ can be directly measured at hadron facilities by Drell-Yan processes with tensor-polarized deuteron ($p + \bar{d} \rightarrow \mu^+\mu^- + X$) [30]. Here, the polarized-proton

![Figure 14. Three kinematical regions of GPDs [28].](image2)

Figure 15. Situation of tensor-polarized PDFs [29].
beam is not needed for investigating this unique spin quantity. The tensor structure has been investigated in the hadron degrees of freedom; however, it begins to be understood in the parton level.

3.4. Spin physics with proton-beam polarization
There is a proposal to polarize the primary proton beam [21]. If it is attained, it becomes a complementary facility to the RHIC-Spin project in the sense that the medium-$x$ region $0.2 < x < 0.7$ can be investigated, whereas the RHIC probes a smaller-$x$ region. For finding each partonic contribution to the nucleon spin, the polarized PDFs should be integrated from 0 to 1, at least from the kinematical region of RHIC to the one of J-PARC. The J-PARC is a unique facility to investigate the polarized antiquark distributions at relatively large $x$. At this stage, there is no reliable flavor decomposition in the polarized antiquark distributions and the polarized gluon distribution has not been determined as shown in Fig. 16. For example, the flavor asymmetric distribution $\Delta \bar{u} - \Delta \bar{d}$ has been measured by the COMPASS collaboration [31]; however, the data are still not accurate enough to distinguish various theoretical models.

The transverse spin of the nucleon is another unsolved problem. By measuring double spin asymmetries of Drell-Yan processes with transversely polarized protons, we should be able to measure transversity distributions which are twist-two structure functions. Because of their chiral-odd property, it does not couple to the gluon polarization, which is unique and quite different from longitudinally-polarized distributions. Therefore, the measurement of the transversity provides us a valuable clue in understanding the nucleon spin. At J-PARC, the transversity distributions can be measured at medium $x$ with the polarized proton beam.

3.5. High-energy hadron reactions in nuclear medium
Apart from the spin studies, there are interesting topics on high-energy hadron reactions. Among them, we briefly discuss parton-energy loss, color transparency, and short-range $NN$ correlations as examples of possible projects. These topics were partially studied at BNL-AGS and Fermilab, so that J-PARC studies should be focused on new developments in this field.

3.5.1. Parton-energy loss

Observation of jet suppression at large $p_T$ is one of major results in heavy-ion collisions at RHIC. This phenomenon is considered to be an evidence of quark-gluon plasma formation because a final-state parton loses energy when it passes through the plasma. However, it is important to test such an energy-loss mechanism in an ordinary nuclear medium instead of the hot medium.

At J-PARC, the Drell-Yan process $p + A \rightarrow \mu^+\mu^- + X$ can be used for such a study [20] as illustrated in Fig. 17. The muon pair is created by the quark-antiquark annihilation ($q\bar{q} \rightarrow \mu^+\mu^-$). Therefore, the parton-energy loss in the initial quark should be observed as an energy loss of the muon pair. Measurements could be done for various energies and nuclear targets, so that their dependencies
should impose constraints on the energy-loss mechanism. This investigation affects the studies on basic properties of quark-gluon plasma in heavy-ion reactions.

3.5.2. Color transparency

Hadron interactions in nuclear medium are important for understanding basic dynamical properties of QCD and for applications to other high-energy hadron interactions. At large momentum transfer, a small-size hadron is expected to freely pass through the nuclear medium. This phenomenon is called color transparency, which should be observed in high-energy hadron reactions. Actual AGS measurements are shown in Fig. 18, where the ordinate is the nuclear transparency defined by $T = \sigma_A/(A\sigma_N)$ with the cross section of $pA \rightarrow pp(A-1)$. As expected, the transparency increases with increasing beam momentum. However, it suddenly decreases at $p > 10$ GeV/c, which is difficult to be interpreted theoretically. At J-PARC, it is interesting to measure the transparency in this region and then to extend the kinematical region to larger energies, where more transparency is expected theoretically as shown Fig. 18.

3.5.3. Short-range nucleon-nucleon correlations

Short-range correlations could be investigated at J-PARC, for example, by the $(p, 2pN)$ reaction as shown in Fig. 19. Here, the 30-50 GeV proton incidents on a nuclear target and two nucleons are emitted on opposite sides in the final state. These nucleons are considered to be close together in the initial state, so that the process is sensitive short-range $NN$ interactions. Observing the reactions with the $pp$ and $pn$ pairs in the final state, we can learn about isospin dependence of the short-range correlations. There are renewed interests in short-range $NN$ interactions, where quark degrees of freedom should play an important role, due to recent developments in lattice QCD [8]. This experimental project is attractive because of a recent finding of strong isospin dependence, namely an unexpectedly large $np$ correlation over the $pp$ ($nn$) one. Two-nucleon short-range correlations are experimentally investigated in proton and electron reactions at BNL and JLab. The results are surprising in the sense that the $np$ correlation is much larger than the $pp$ one as shown in Fig. 20 [33]. It could be explained by the tensor force in the $NN$ interaction. Such a difference between the $pn$ and $nn$ correlations could affect neutron-star properties since a certain fraction of protons exists in the stars. At J-PARC, it is valuable to study unexplored three-nucleon correlations at J-PARC in addition to the two-nucleon ones.

4. Summary

The first stage of the J-PARC facility has been completed and hadron-physics experiments have begun. We introduced some of the major projects in this article, first the approved experiments on strangeness hadron physics and mass modifications in the nuclear medium, and second the future possibilities of hadron-structure physics. In the beginning, new discoveries are expected for new hypernuclei, hyperon interactions, kaonic nuclei, exotic hadrons with strangeness, and mechanism of hadron-mass generation. In the next stage, the various aspects of
hadron structure could be investigated in addition. The possibilities of this second-stage projects were focused in this article. The topics include flavor dependence of antiquark distributions, transverse-momentum-dependent distributions such as the Boer-Mulders and Sivers functions, polarized exclusive reactions, tensor structure functions, and generalized parton distributions. Furthermore, high-energy parton and hadron reactions could be also investigated in nuclear medium. Among them, parton-energy loss, color transparency, and short-range corrections were discussed. These topics were introduced in this article just as examples of future projects on hadron structure at J-PARC. Better ideas and actual proposals are essential for the success of future J-PARC hadron project.

Acknowledgements
This work was partially supported by the Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology.

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