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Hadron physics at J-PARC

Megumi Naruki*

High Energy Accelerator Research Organization, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan
*E-mail: megumi.naruki@kek.jp

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Hadron spectroscopy and dilepton measurement are essential parts of the hadron physics programs at the J-PARC hadron facility, which is designed as a multipurpose experimental facility for a wide range of particle and nuclear physics programs. The topics of interest are hadron structure, the search for exotic states, and medium modification of the vector meson mass. As the first experiment, the search for the Θ^+ pentaquark via a pion-induced hadronic reaction began in the autumn of 2010. Programs to use the kaon beam will start in the autumn of 2012, in accordance with the increase of beam power. Of the various experimental programs concerning hadron physics, only selected topics are briefly described here.

1. Introduction

Quantum chromodynamics (QCD) is believed to be the basic theory of the strong interaction at every energy scale. However, aspects of QCD vary greatly by energy owing to the large energy dependence of the running coupling constant. At short distances, a perturbative treatment is available between quarks and gluons as a result of asymptotic freedom. However, at large distances, the non-Abelian character of QCD plays an important role in constructing hadronic systems where quarks and gluons strongly interact. Even though an analytical approach based on the QCD Lagrangian is difficult to implement in the low-energy regime, there are rich phenomena to delineate the essential characteristics of QCD.

One of the key issues of QCD at low energy is the problem of confinement. Colored quarks and gluons are confined inside a colorless hadron; therefore, they cannot be observed as a single particle in experimental detectors. The confinement is closely related to the structure of the QCD vacuum. A familiar explanation for confinement is that the color-electric flux between quarks is squeezed into a tube carrying energy that linearly increases with length; thus the tube is more likely to break into shorter tubes rather than a single color charge at the long-range regime. This means that one property of the QCD vacuum is to expel the color-electric flux, analogously to the Meissner effect in superconductors. This picture is intuitively appealing to us; however, there seems to be no generally accepted theory of confinement. The QCD vacuum is characterized by a quark condensate to which the spontaneous breaking of chiral symmetry is attributed. It is almost universally believed that the constituent quark masses are generated as a consequence of chiral symmetry breaking. The hadron is well described as a bound state of constituent quarks, which typically obtain extra mass of several hundred MeV inside the hadron. For example, the constituent masses of u and d quarks are of order 300 MeV, whereas the current quark mass is only a few MeV. Given the fact that the pion can be understood as the Nambu–Goldstone boson associated with chiral symmetry breaking, this is a plausible explanation for the origin of hadron mass. Recently, lattice QCD calculations have shown that quark condensation is realized in the QCD vacuum. However, there seems to be no theoretical or experimental proof of the mechanism for generating hadron mass.

There is a great opportunity to investigate these problems using high-intensity hadron beams at J-PARC. Many programs in the field of hadron physics are planned and are being performed at the J-PARC hadron facility. A summary of the proposed experiments can be found in Ref. [1]. In this manuscript, I present selective topics especially related to the hadron structure and the mass modification of the vector mesons. It is important to describe the hadron as a bound state of quarks based on QCD to understand the confinement mechanism. One way to approach this is with hadron spectroscopy, since the mass and decay width of the hadron are reflected by the interaction between quarks and gluons inside. It is especially advantageous to study exotic states, whose properties could be a distinctive consequence of the quark–quark interaction. The study of exotic, new hadronic states will shed light on quark dynamics at low energy. Currently, searches are planned for multiquark states such as the Θ^+ pentaquark and the H-dibaryon, deeply bound kaonic nuclei, and a candidate for the $\bar{K}N$ bound state $\Lambda(1405)$. The mass of the vector meson could be modified as a consequence of the spontaneous breaking of chiral symmetry. The mass modification of the vector meson in the nuclear medium is systematically investigated in a variety of experimental programs here at J-PARC. In the following section, each experimental program is briefly described.

2. Search for exotic hadrons

2.1. Search for the Θ^+ pentaquark

Quantum chromodynamics allows for any multiquark system, as long as it is colorless. Therefore, intensive searches for "exotic hadrons," particles that consist of four or more quarks, have been made for over 30 years. In 2003, the LEPS Collaboration observed a narrow resonance at 1540 MeV/c^2 in the K^- missing-mass spectrum for the $\gamma n \to K^+K^-n$ reaction on a carbon target [2]. This new particle, named the Θ^+ pentaquark, contained four quarks and one antiquark. Θ^+ is the first explicitly exotic hadron that has irreducible quark components, $uudd\bar{s}$. Many positive results were reported from various reactions [2–12], whereas negative results were reported from many high-energy experiments with high statistics [13–23] and from low-energy experiments [24–27]. The positive results were reexamined in dedicated experiments or using improved analyses; some of them were confirmed [28,29] and others turned out to be not significant enough to claim evidence of Θ^+ [30–32]. The existence of Θ^+ is not yet confirmed and today remains an urgent problem in hadron physics.

The J-PARC E19 experiment was proposed to search for the pentaquark Θ^+ in the $\pi^-p \to K^-X$ reaction [33]. It should be noted that searches for Θ^+ were performed in π- and K-induced reactions at KEK-PS. In the E522 experiment, a search for Θ^+ in the $\pi^-p \to K^-X$ reaction was made [35]. A bump structure at the mass of Θ^+ in the missing-mass spectrum was observed, as shown in Fig. 1(left). However, the statistical significance was 2.5σ, which was not large enough to claim an observation. The upper limit obtained for the differential cross section was 2.9 μb/sr in the laboratory frame at 90% confidence level (C.L.). The E559 experiment searched for Θ^+ in the $K^+p \to \pi^+X$ reaction. No peak was found in the missing-mass spectrum, as shown in Fig. 1(right). The 90% C.L. upper limit was given as 3.5 μb/sr in the laboratory frame. By taking the CLAS [25] and E559 [34] results into consideration, the coupling of Θ^+ to K^*N should be very small compared with that of Θ^+ to KN. Therefore the main production process in the $\pi^-p \to K^-\Theta^+$ reaction is the s channel in which Θ^+ is produced via the neutron or N^* as an intermediate state. The process has no strong angular dependence and the cross section is proportional to the decay width of Θ^+. This narrow width is a striking feature of Θ^+, making it very attractive for experimental searches but difficult to

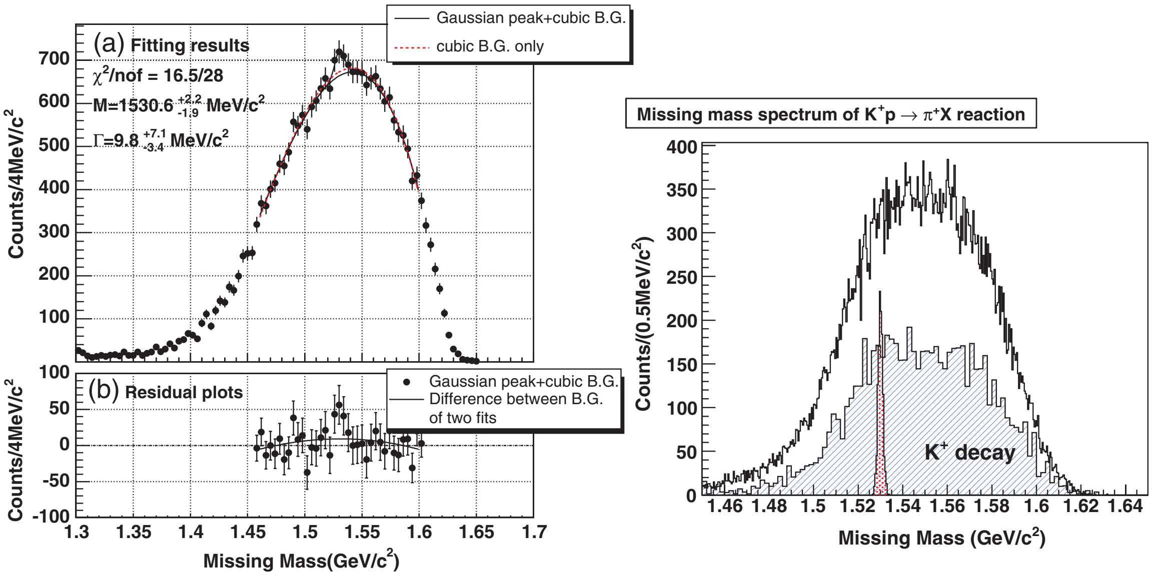

Fig. 1. Left: Missing-mass spectrum of the $\pi^- p \to K^- X$ reaction with a polyethylene target at a beam momentum of 1.92 GeV/c measured in the E522 experiment [35]. The solid line is the fit result with a Gaussian peak and a polynomial background. Right: Missing-mass spectrum of the $K^+ p \to \pi^+ X$ reaction measured in the E559 experiment [34]. The hatched histogram shows empty target data; the dotted spectrum is the expected signal assuming a zero width, a total cross section of 50 μb, and an isotropic production of π^+ in the CM system.

explain by a theory. Θ^+ is searched for in the (π^-, K^-) reaction on a liquid-hydrogen target with the missing-mass technique. The expected sensitivity reaches 75 μb/sr in the laboratory frame. We aim to study the production process of Θ^+ and determine the decay width from the cross section with high statistics and high resolution. This is the first experimental program to be performed at the J-PARC hadron facility.

The first physics run was performed from October to November 2010 at the K1.8 beamline, which provides secondary beams whose momentum is up to 2 GeV/c. The beam momentum was set to 1.92 GeV/c, the same as the past KEK experiment, to examine the significance of the structure observed in the E522 experiment. The typical beam intensity was $\sim 10^6$ pions/pulse with a duty factor of 16%. The 7.8×10^{10} beam pions irradiated the liquid-hydrogen target, whose interaction length is 0.86 g/cm^2. The beam particles were analyzed with the beam spectrometer, and the scattered kaon was detected with the superconducting kaon spectrometer (SKS), which provides a momentum resolution of 0.2% (FWHM) with a wide acceptance of 100 msr. The spectrometer performance was studied with Σ^+ production. The obtained missing-mass resolution in the $\pi^+ p \to K^+ X$ reaction is 1.9 MeV (FWHM), which corresponds to a resolution of 1.4 MeV (FWHM) for the Θ^+ production case. The details of the beamline and SKS spectrometer are described elsewhere [36]. The overall efficiency and detector acceptance were examined with the production cross section of Σ^+. Our data are consistent with the past measurement [37]. Figure 2 shows the missing-mass spectrum of the $\pi^- p \to K^- X$ reaction [38]. No corresponding structure is observed at the Θ^+ mass region of 1.51–1.55 GeV/c^2. The data can be described with a simulated background from the known production of ϕ and $\Lambda(1520)$ together with three-body phase space. After the acceptance correction is made, the data were fitted with a Gaussian peak and a polynomial background as shown in Fig. 3(a). Figure 3(b) shows the differential cross section of the $\pi^- p \to K^- \Theta^+$ reaction. The upper limit obtained for the differential cross section is 0.26 μb/sr at a 90% C.L. in the mass range of 1.51–1.55 GeV/c^2. The obtained upper limit is smaller by an order of magnitude compared with that of

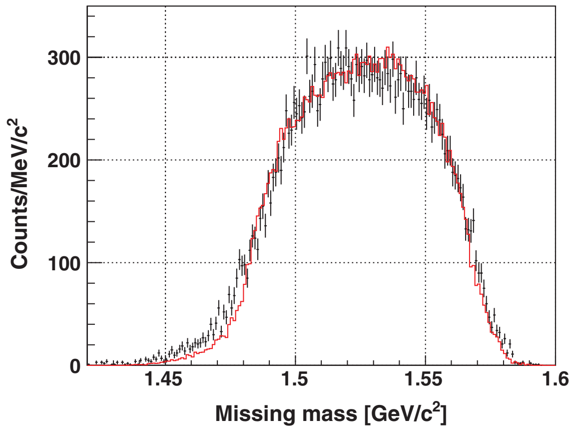

Fig. 2. Missing-mass spectrum of the $\pi^- p \to K^- X$ reaction measured in the E19 experiment [38]. Acceptance is not corrected for. The data points are shown with error bars. The histogram is a simulated background from the known sources.

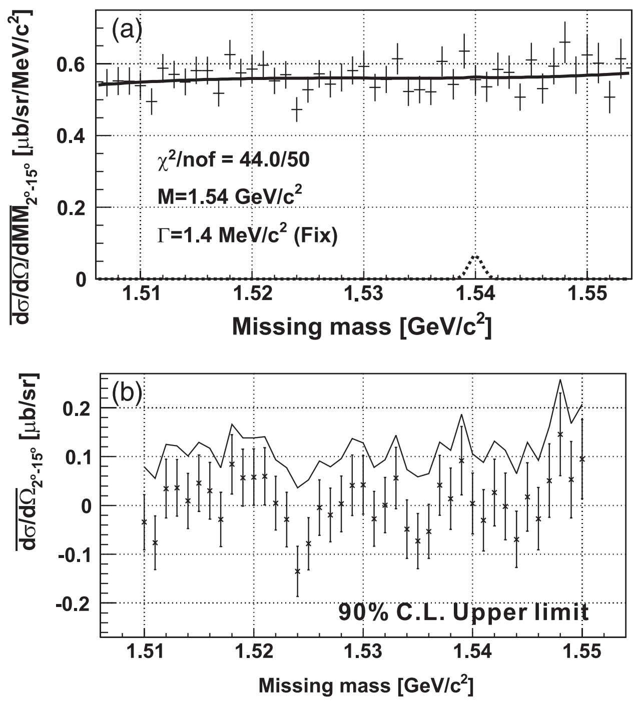

Fig. 3. (a) Missing-mass spectrum of the $\pi^- p \to K^- X$ reaction after acceptance correction [38]. The solid line shows the fit result with a Gaussian peak and a third-order polynomial background. A possible peak with a 90% confidence level is drawn at a mass of 1.54 GeV/c^2 as a dotted line. (b) Differential cross section of the $\pi^- p \to K^- \Theta^+$ reaction. The 90% confidence level upper limit of the differential cross section is indicated with a black line. See Ref. [38] for details.

the previous KEK experiment. The upper limit of the differential cross section can be translated into an upper limit of the decay width with the help of a theoretical calculation [39]. It is estimated to be 0.72 and 3.1 MeV for $J^P_\Theta = 1/2^+$ and $J^P_\Theta = 1/2^-$, respectively.

In February 2012, the second physics data-taking run was carried out at a beam momentum of 2 GeV/c. The accumulated beam pions amounted to 8.7×10^{10}. Since the cross section is expected to increase according to the beam energy from the theoretical prediction, a stricter upper limit for the decay width will be given by the new data.

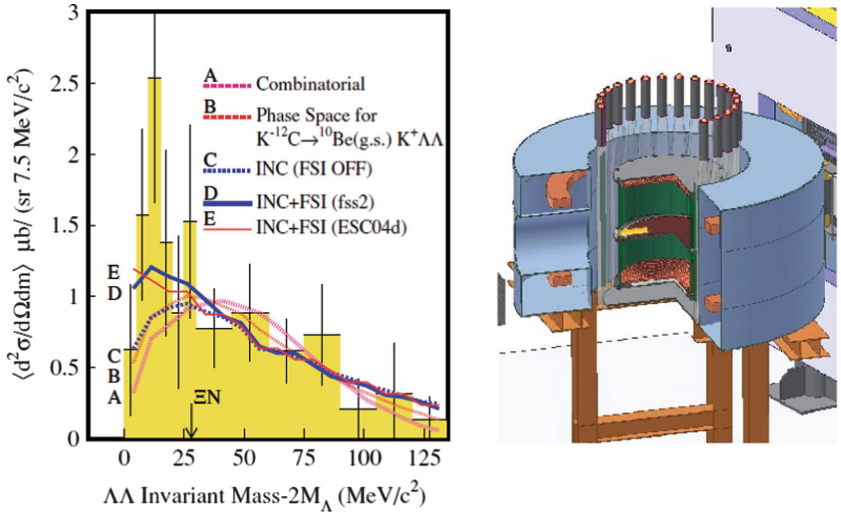

Fig. 4. Left: Invariant-mass spectrum of $\Lambda\Lambda$ measured in the E522 experiment [49]. Lines are theoretical predictions and experimentally deduced background. Right: Schematic view of the TPC inside a superconducting magnet designed for the J-PARC E42 experiment [50].

2.2. Search for the H-dibaryon

High-intensity kaon beams enable us to study new hadronic systems that exhibit single or multi-strangeness. The H-dibaryon, which is a six-quark state $uuddss$, was first proposed by Jaffe [40] based on the MIT bag model. Since then, many theoretical and experimental efforts have been made to seek evidence of its existence. See Refs. [43,44] for more details. Although there has been some indication from the experimental works to address the existence of the H-dibaryon [45,46], nothing has been conclusive so far. Enhancement was observed in the $\Lambda\Lambda$ invariant-mass spectra near the threshold produced in the $^{12}C(K^-, K^+)$ reaction, as shown in Fig. 4(left) [48,49]. However, it is pointed out that the enhancement can be understood by the attractive $\Lambda\Lambda$ interaction within the present statistics. Recently, the possible existence of the H-dibaryon has been announced by the HAL QCD and NPLQCD Collaborations based on full lattice QCD calculations. One has to keep in mind that the result is obtained at a pion mass of ∼390 MeV or larger, still far from the physical point. However, an extrapolation of two results suggests the existence of the H-dibaryon as a weakly bound or resonant state.

A new experiment has recently been proposed aimed at providing a distinct conclusion for the existence of the H-dibaryon in the $\Lambda\Lambda$ invariant-mass spectrum. The H-dibaryon will be searched for in the (K^-, K^+) reaction at the K1.8 beamline at a beam momentum of 1.8 GeV/c. The beam kaon is identified with the beamline spectrometer, and the scattered K^+ is identified with the KURAMA spectrometer. In addition, a newly developed time projection chamber (TPC) will be installed just before the KURAMA magnet to detect the decay products of Λ and also H. It provides a mass resolution of 1.0 MeV. TPC research and development is now ongoing. A schematic view of the TPC is shown in Fig. 4 (right). The expected yield of the $\Lambda\Lambda$ events is about 100 times larger than that of the past KEK experiment.

2.3. Search for deeply bound kaonic nuclei

The K^-pp system was proposed by Akaishi and Yamazaki based on the $\Lambda(1405)$ ansatz [71], in which the $\Lambda(1405)$ is assumed to be an $I = 0$ quasibound state of $\bar{K}N$ resulting from the strong

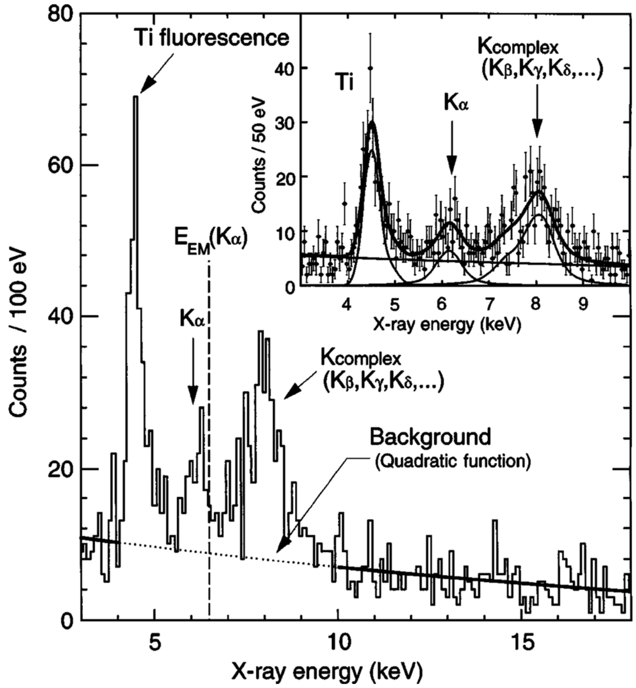

Fig. 5. Kaonic hydrogen x-ray spectrum measured in the KpX experiment. The inset shows the fit result. The peak of K_α ($2p$ to $1s$) is shown at the lower side of the pure electromagnetic value $E_{EM}(K_\alpha)$. The figure is reproduced from Ref. [55]. Copyright (1997) by the American Physical Society.

interaction between $\bar{K}$ and the nucleon [52–54]. The basic hadronic $\bar{K}N$ interaction has been studied through kaonic atom x-ray measurements, which provide information on the energy-level shift and width of the state. The KpX experiment first observed the repulsive energy-level shift in the kaonic-hydrogen $1s$ atomic state [55], as shown in Fig. 5. It was subsequently confirmed by the DEAR [56] and SIDDHARTA experiments [57]. These results suggest that the isospin $I = 0$ s-wave $\bar{K}N$ is quite strongly attractive, whereas the interaction is weakly repulsive in a KN system. Data from x-ray spectroscopy, especially for the kaonic helium atom, would be a test of the strongly attractive $\bar{K}N$ potential proposed by Akaishi and Yamazaki, since they predicted a large shift of the kaonic ^{3}He and ^{4}He atoms [51], whereas other theories predicted almost zero shift [58–60]. Recently, the SIDDHARTA experiment reported a result consistent with zero for the shift of the kaonic ^{3}He $2p$ state. A more precise measurement of the isotope shift in the kaonic ^{3}He and ^{4}He atoms is planned at the K1.8BR beamline in the E17 experiment with a precision of better than 1 eV.

Properties such as mass and width of kaonic nuclei are expected to be influenced by the strength of the basic $\bar{K}N$ interaction. For example, the binding energy of the K^-pp system varies from 20 to 130 MeV among theoretical predictions [52–54,61–65]. The deepest binding energy is obtained with a Skyrme model; in contrast, rather shallow binding is calculated in a theoretical model based on chiral SU(3) dynamics pronouncing the two-pole structure of $\Lambda(1405)$ [70,73]. Experimental information on the properties of kaonic nuclei is important for describing the $\bar{K}N$ interaction in the very low energy region. It has also been pointed out that a kaonic nucleus would be an extremely dense system [74]. $\bar{K}$ plays a key role in kaonic nuclei forming such dense matter owing to the strong $\bar{K}N$ attraction in balance with the hard-core nucleon–nucleon repulsion. Kaonic nuclei possibly have extremely high density, exceeding a few times that of the average ($\rho_0 = 0.17$ fm^3), thus making them interesting in the context of chiral symmetry restoration at high density.

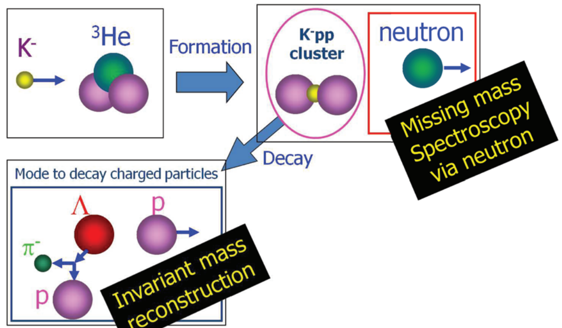

Fig. 6. Schematic illustration of the E15 experiment. The K^-pp system is searched for in the invariant-mass spectrum and also in the missing-mass spectrum.

In experimental work, the FINUDA Collaboration first suggested the observation of the K^-pp state in the invariant-mass spectrum of Λ and the proton in K^- absorption reactions on nuclear targets (^{6}Li, ^{7}Li, and ^{12}C) [66]. In the following couple of years, the possible existence of the K^-pp system was reported by the OBELIX Collaboration [67] and more recently the DISTO Collaboration [68]. They reported a remarkably deep binding energy of 103–161 MeV and a width of 24–118 MeV. However, there seems to be no consensus among these experiments and thus currently nothing is conclusive. Under such situations, new experimental data using the elementary $\bar{K}$-induced reaction are eagerly awaited.

At the J-PARC hadron facility, the deeply bound kaonic nuclear state is searched for in the E15 experiment with a helium-3 target at the K1.8BR beamline [69]. The in-flight kaon reaction is exclusively measured in the reaction ^{3}He$(K^-, n)K^-pp$. The bound state is searched for both in the invariant-mass spectrum of the decay products of the K^-pp system and in the missing-mass spectrum with an escaping neutron, as illustrated in Fig. 6. The beam kaon is analyzed with the beamline spectrometer, described in detail elsewhere [69]. The decay particles of K^-pp are measured with a cylindrical detector system (CDS) [69]. The liquid ^{3}He target is located at the center of the CDS. Particle tracking is performed with a cylindrical drift chamber, surrounded by a hodoscope, which is used as a charged-particle trigger and particle identification with the time-of-flight (TOF) technique. The components are enclosed within a solenoid magnet, which provides a field of 0.7 T at maximum. A neutron is detected with an array of scintillators placed 15 m apart from the final focus point, where the target system is located. The beam particles are swept out to a beam dump with a dipole magnet to eliminate charged particles going through the neutron counter. All the detectors together with the target are installed and their performance has been examined through a commissioning run. The background and the performance of the CDS were examined through Λ production by detecting the decay particles of π^-s and protons in the winter of 2011. Figure 7 shows a reconstructed peak of Λ with a good signal-to-noise ratio. The first production run will be performed in the autumn of 2012.

The K^-pp is also searched for in the π-induced reaction $d(\pi^+, K^+)$ at the K1.8 beamline with the SKS in the E27 experiment. This is a unique method for producing K^-pp through a doorway state of $\Lambda(1405)$ using the 1.7 GeV/c pion beam currently only available at the K1.8 beamline. Since suppressing the background originating from the quasifree process is crucial for this measurement, a method is applied to tag two high-momentum protons in the final state, which is a distinct feature

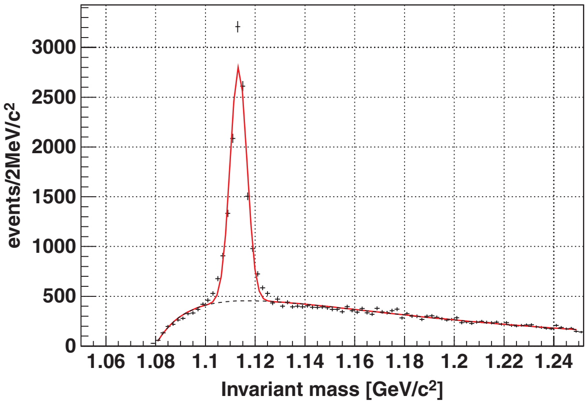

Fig. 7. Invariant mass of $\pi^- p$. The clear peak of Λ is shown. The solid line is the fit result with a Gaussian peak and an empirical curve for the background.

of the $K^- pp$ decay. In the spring of 2012, the effectiveness of the method was examined with a preparatory run by installing range counters developed for the experiment.

2.4. Structure of $\Lambda(1405)$

The structure of $\Lambda(1405)$ is closely related to the existence and properties of kaonic nuclei. $\Lambda(1405)$ has been thought to be a candidate for an exotic hadronic state, mainly because the mass splitting between $\Lambda(1405)$ and $\Lambda(1520)$ is unlikely to be large in the quark model classification. One traditional interpretation is a $\bar{K}N$ bound state. The mass of $\Lambda(1405)$ lies 30 MeV below the $\bar{K}N$ threshold. It has been debated for many years whether $\Lambda(1405)$ can be described with a three-quark state or a $\bar{K}N$ bound state, or even an intrinsic pentaquark state. Although it is experimentally a well-established state, a detailed investigation is necessary to give an definite answer to the dynamics of $\Lambda(1405)$.

Recently, it was pointed out that the line shape of $\Lambda(1405)$ depends on the production process and also the decay channels [75–77] (see also Ref. [78]). In the chiral unitary approach, it is shown that $\Lambda(1405)$ has a two-pole structure that has different couplings to the $\pi\Sigma$ and $\bar{K}N$ channels, thus the $\pi\Sigma$ invariant spectra could be modified depending on the initial channels $\pi\Sigma$ and $\bar{K}N$. Moreover, the line shape of $\Lambda(1405)$ depends on the charge states of decay channels. The interference term between $\pi\Sigma$ states with isospin $I = 0$ and $I = 1$ gives a significant difference in the $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ spectra. The line shape of $\Lambda(1405)$ will be studied for all decay channels ($\Sigma^+\pi^-$, $\Sigma^-\pi^+$, and $\Sigma^0\pi^0$) in the (K^-, n) reaction on a deuterium target in the E31 experiment. It is important to measure these channels precisely and simultaneously to extract experimental information on the pure $I = 0$ contribution. The $d(K^-, n)$ reaction is expected to enhance s-wave $\bar{K}N$ scattering below the $\bar{K}N$ threshold to form a $\Lambda(1405)$ at a forward angle of the scattered neutron. The structure of $\Lambda(1405)$ can be studied through understanding the dynamics that lead to its formation. The detector system is the same as that of the E15 experiment, except for the deuterium target and two additional detectors (a plastic scintillator and a multiwire drift chamber) used for identifying protons emitted backward in $\Lambda(1405)$ decay. The layout of the experimental setup is shown in Fig. 8. The scattered neutron is measured with the TOF counter described above, and the decay particles of $\Lambda(1405)$ are measured with the CDS together with additional hodoscopes and chambers. Since the yield is expected to be large enough with a K^- beam whose intensity is $\sim$10% of the full beam power, the experiment will be carried out at an early stage at J-PARC.

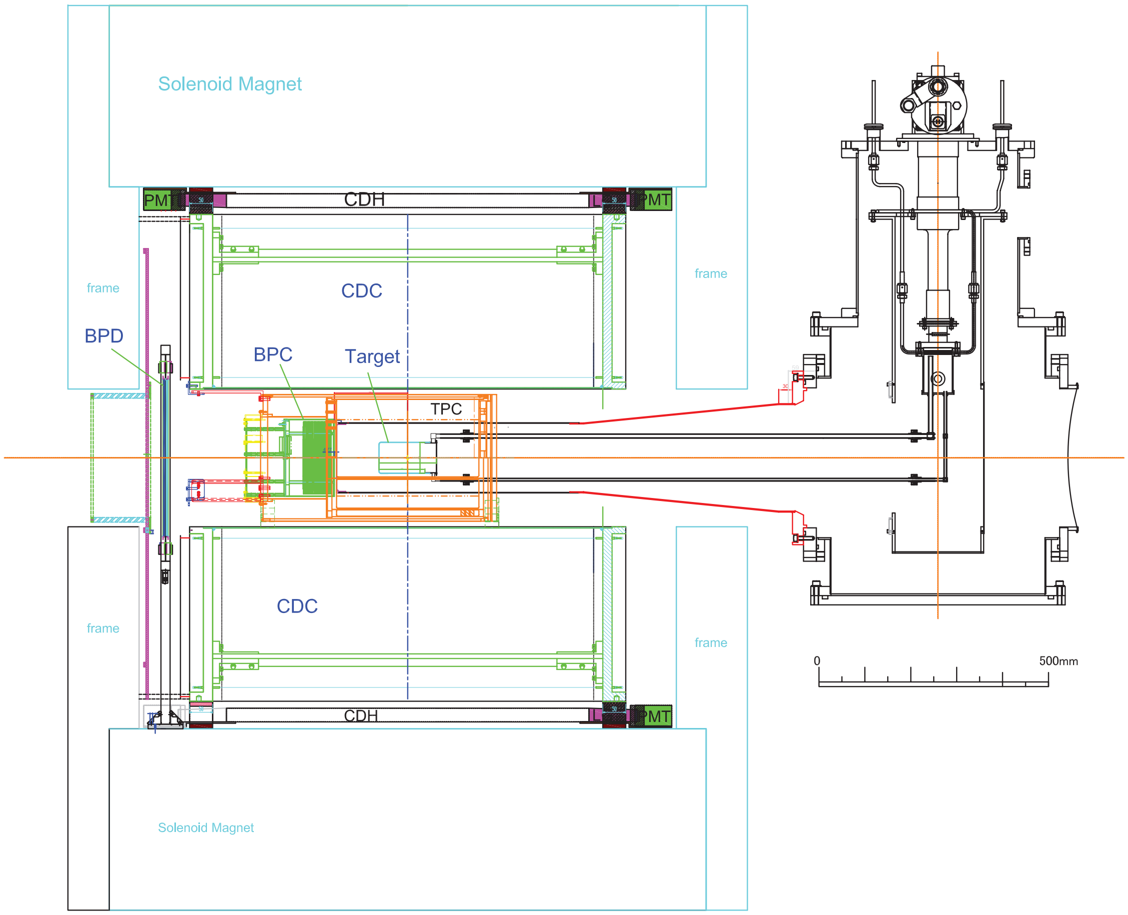

Fig. 8. Schematic view of the setup for the E31 experiment.

3. Using the vector meson mass to explore chiral symmetry

Besides hadron spectroscopy, the origin of the hadron mass is another major topic at the J-PARC hadron facility. It is widely believed that most of the light hadron mass is generated through the spontaneous breaking of chiral symmetry. For the light quarks u, d, and s, the constituent quark has a mass of a few hundred MeV, whereas the current quark mass is only a few MeV. In the QCD vacuum, spontaneous chiral symmetry breaking causes quark–antiquark pair condensation and generates the dynamical mass of the quarks. At high temperature and/or high density, chiral symmetry is sure to be restored and the properties of the hadron would be modified from those in the vacuum. Since the chiral condensate itself is not observable, we need a link between chiral symmetry breaking and a hadron mass that can be measured in the real world. Partial restoration of the symmetry is experimentally indicated from measurement of a deeply bound pionic atom [80], through theoretical work showing that the chiral order parameter can be translated from the pion-nucleus scattering length [79]. Also, it has been pointed out that the vector meson mass would be modified in consequence of chiral symmetry breaking in hot, dense matter in Refs. [81–83] and many other theoretical works. One can examine whether the hadron mass originates from chiral symmetry breaking through the measurement of the vector meson mass.

Experimental research concerning the modification of the hadron mass has been done in a variety of facilities worldwide. In the pioneering work done in the CERES/NA45 experiment, the enhancement at the low-mass side of ρ and ω mesons in the dielectron measurement produced in Pb–Au

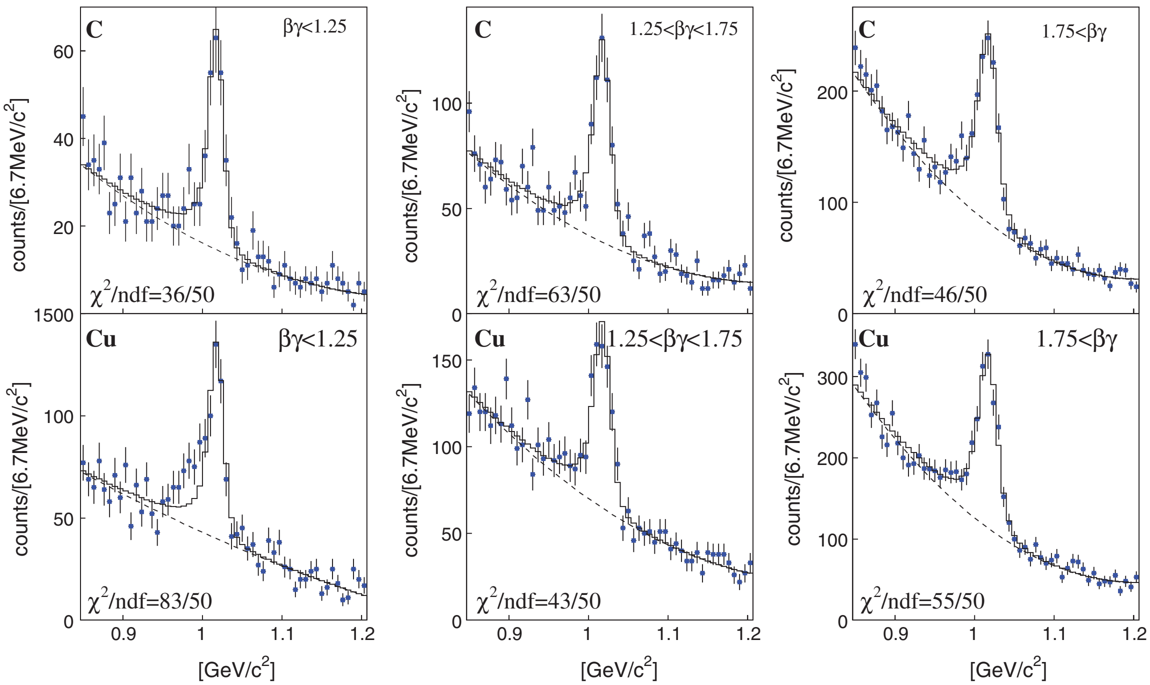

Fig. 9. Invariant-mass spectra of e^+e^- pairs measured in the KEK-PS E325 experiment. The data points are shown with error bars. The solid lines show the fit results with the polynomial backgrounds indicated with dashed lines and simulated shapes of the in-vacuum ϕ meson, in which all experimental effects are taken into account. The figure is taken from Ref. [88].

collisions at 158 AGeV was reported [84]. The succeeding experiment, NA60, measured muon pairs in 158 AGeV In–In collisions at the CERN SPS. In that experiment all known sources and background from the observed spectrum were subtracted and the remaining signal was consistent with the broadening of the ρ meson [85]. There are a variety of theoretical interpretations taking into account many-body effects in heavy-ion collisions [86]. A low-mass enhancement was observed in the PHENIX experiment on the e^+e^- spectrum measured in $\sqrt{s} = 200$ GeV Au + Au collisions [87]. Currently, none of the theoretical models employed to reproduce the data at the SPS can describe the enhancement observed by PHENIX.

A dilepton measurement was done at rather low energy to investigate the hadron mass modification in cold nuclear matter. While a drastic change of $\langle \bar{q}q \rangle$ is expected at or above a critical temperature, the system evolves dynamically in heavy-ion collisions, thus making any theoretical interpretation difficult. Normal nuclear matter is a static system, and a sizable effect of chiral symmetry restoration is expected even at the normal nuclear density since $\langle \bar{q}q \rangle$ linearly decreases with density. The KEK-PS E325 experiment observed the modification of ρ, ω, and ϕ mesons in the nuclear medium on the invariant-mass spectra of e^+e^- pairs in 12 GeV $p + A$ interactions [88,89]. A large enhancement is observed at the low-mass side of the ρ and ω mesons with a significance of $\sim 10\sigma$ [89]. This enhancement can be reproduced with a model in which the mass of ρ and ω decreases by 9.2% with no width broadening. Figure 9 shows the invariant-mass spectra of e^+e^- pairs for carbon and copper targets. Clear peaks of the in-vacuum ϕ meson are seen in all momentum regions for both sets of target data. Only in the low-momentum region of the copper target data, where the ϕ meson is expected to have a larger probability of decaying inside the nucleus, is the enhancement over the unmodified shape observed. The observed modification can be described with a model in which the mass of the ϕ meson decreases by 3.4% and the decay width broadens by 3.6 times at the normal nuclear density. The observed mass modifications of the ρ and ω meson and also the ϕ meson are consistent with the theoretical prediction based on the in-medium QCD sum rule [81].

The CBELSA/TAPS Collaboration reported a mass modification of the ω meson measured in the $\gamma + A \to \omega + X \to \pi^0\gamma + X$ reaction on a Nb target [90]. It is advantageous to use the decay channel of $\omega \to \pi^0\gamma$ since one can address the modification of ω apart from the ρ, which is always overlapped on the dilepton measurement. However, one should treat the final-state interaction between the hadronic decay product and the target nucleus carefully. The high-momentum π^0s were selected to eliminate the effect of final-state interaction. The enhancement was explained with an 8% mass decrease in nuclei at first, but later it was found to be statistically marginal in the reanalysis [91]. From the analysis of the transparency ratio, the absorption cross section of the ω is deduced and it is converted into the additional width in the nuclei, which is thought to be increased by a factor of 30 at the normal nuclear density [92].

The medium modification for ρ and ω was not observed in the invariant-mass spectrum of e^+e^- pairs produced in photoproduction measured by the CLAS Collaboration [93]. The extracted ρ line shape is consistent with the model calculation if the collisional broadening inside the target nucleus is taken into account.

3.1. Dilepton measurement in the nuclear medium

The E16 experiment aims at obtaining experimental evidence for the onset of chiral symmetry restoration in nuclear matter. The experiment will be performed at the high-momentum beamline, which is expected to be constructed by the end of fiscal year (FY) 2015 at the Hadron Experimental Facility. The beamline can provide 30 GeV primary protons branched off at the middle of the switch-yard with a typical intensity of 10^{10}–10^{12} protons/pulse. The matter-size dependence of the mass modification is planned to be studied using various targets (CH_2, C, Cu, and Pb). It is crucial to use a thin target to suppress the background originating from the γ conversions and also the radiative tail associated with the bremsstrahlung in the target material. A schematic view of the spectrometer is illustrated in Fig. 10. The electrons are identified with a newly constructed spectrometer that has an acceptance 5 times larger than that of E325. The particle trajectory is measured with the GEM tracker to realize high resolution under a high interaction rate, which is typically 10 MHz. The electron identification is performed with the hadron blind detector (HBD) originally developed for the PHENIX experiment. The HBD is filled with CF_4 gas, which works as a Cherenkov radiator, and an amplification gas with a photocathode to amplify the photoelectrons. The photocathode consists of a GEM stack, on top of which a CsI is evaporated. The yield of $\phi \to e^+e^-$ events is estimated to be 10^5 for each target. With these statistics, the momentum and nuclear size dependence of the ϕ meson mass can be studied systematically.

3.2. Direct measurement of the ω mass modification

Measurement of the direct ω mass modification is planned at the K1.8 beamline in the E26 experiment. In this program, ω mesons are produced in $\pi^- + A$ reactions and reconstructed in the $\pi^0\gamma$ decay on a invariant-mass spectrum using a gamma-ray detector. At the same time, escaping neutrons are identified with a neutron counter to perform missing-mass spectroscopy in the $A(\pi^-, n)\omega$ reactions. From the missing-mass spectroscopy information, one can address the mass modification of the ω meson, which is slowly moving or rather bound inside the nucleus.

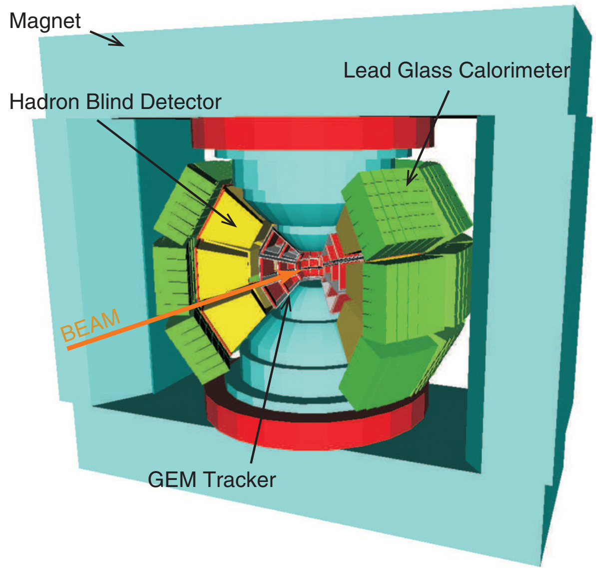

Fig. 10. Schematic view of the E16 spectrometer.

3.3. ϕ mesic nuclei

One way to determine the strength of the ϕ meson mass decrease in nuclei is to produce only slowly moving ϕ mesons, where the maximum nuclear matter effect is expected. The observed mass reduction of the ϕ meson in the nucleus can be translated as the existence of an attractive force between the ϕ meson and the nucleus. Thus, one of the extreme conditions that can be achieved in the laboratory is indeed the formation of a ϕ-nucleus bound state, where the ϕ meson is "trapped" in the nucleus. The purpose of the experiment is to search for a ϕ-nucleus bound state and measure the binding energy of the system. It is demonstrated that a completely background-free missing-mass spectrum can be obtained efficiently by $(\bar{p}, \phi)$ spectroscopy together with $K^+\Lambda$ tagging, using the primary reaction channel $\bar{p}p \rightarrow \phi\phi$. This measurement has been planned as the E29 experiment.

4. Summary and outlook

The hadron structure, the search for exotic states, and medium modification of the vector meson mass are topics covered by the hadron physics programs at the J-PARC hadron facility. The first experiment, E19, conducted at the K1.8 beamline with the SKS spectrometer, aimed to search for the pentaquark Θ^+ in the $\pi^- p \rightarrow K^- X$ reaction. No corresponding structure has been observed on the missing-mass spectrum of the $\pi^- p \rightarrow K^- X$ reaction. The upper limit of the differential cross section obtained is 0.26 μb/sr in the laboratory frame. A search for kaonic nuclei will be performed at the K1.8BR beamline using the kaon beam in the autumn of 2012. Properties of the $K^- pp$ system will be studied in both the invariant-mass spectrum and the missing-mass spectrum. The dilepton measurement will be carried out at the high-momentum beamline, which provides primary protons up to 10^{12} particles/pulse. The momentum dependence of the medium modification of the vector meson mass will be systematically studied with various target materials. The variety of secondary beamlines at the J-PARC hadron facility provides a great opportunity to perform experimental studies at the leading edge of hadron physics research.

Finally, I would like to mention an expansion of the hadron hall that is planned for the near future. New characteristic beamlines will be constructed at a new hall with a second production target. For example, under intense discussion is a realistic design for a high-momentum secondary beamline that can transport secondary particles up to 10 GeV/c. A high-momentum kaon beam would enable us to study multistrange hadrons systematically. A high-intensity, high-resolution beamline can be realized with a dispersion matching technique for precise spectroscopy of hypernuclei and mesic nuclei. The expansion will give us fruitful results for hadron physics.

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