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# Towards the Measurement of the Mass Modifications of Vector Mesons in a Finite Density Matter

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An experiment is being carried out at J-PARC — Japan Proton Accelerator Research Complex — to study the origin of hadron mass and the partial restoration of chiral symmetry of quantum chromodynamics in a finite density matter. The experiment, which is called the J-PARC E16 experiment, aims to measure the mass spectra of vector mesons in nuclei due to finite density effects. Previous measurements were performed at KEK-PS proton synchrotron and showed mass modifications of vector mesons in nuclei. A new experiment aims to confirm the results of KEK-PS with larger statistics to have a detailed study. Mass spectra of vector mesons are measured using electron–positron decays in proton-nucleus reactions. A new beam line is built to provide a high-intensity proton beam for the experiment, and decayed electrons and positrons are detected and identified by a newly constructed spectrometer. The experiment started the acquisition of pilot data to evaluate the performances of the beam line and the spectrometer in 2020 and 2021. The spectrometer worked well, and physics data taking will start in 2023.

topics: hadron mass, chiral symmetry, vector mesons, finite density matter

## 1. Introduction

One of the most important research topics in the field of nuclear physics is the origin of the hadron mass. There is a huge discrepancy between the mass of bare quarks and hadrons. A proton, which contains three light quarks, has a mass of $\sim$ 940 MeV/$c^2$, however, light quarks only have a "bare" mass of a few MeV/$c^2$. This discrepancy between quark mass and hadron mass is an interesting phenomenon to be understood.

The origin of large hadron mass is explained as a dynamical mass generation caused by a spontaneous breaking of chiral symmetry in a "vacuum" [1]. Here, the chiral symmetry is an approximated symmetry of quantum chromodynamics and plays essential roles in aspects of hadron physics. So, it is important to understand the properties of chiral symmetry to study the origin of hadron mass. In particular, it is predicted that the symmetry can be partially restored in a finite temperature and/or density medium, and the study of such media can give a piece of crucial information on chiral properties in the medium. For example, an order parameter of the restoration is evaluated theoretically as a function of the temperature and density of the medium [2, 3].

When the symmetry is restored in a created matter, the properties of a hadron in the matter also can be changed. For example, several experiments are performed using meson–nucleus bound states to study hadron properties in a finite density matter [4]. In particular, mass spectra of vector mesons have important information for the restoration of symmetry in matter. Quark–antiquark condensates, which are order parameters of the symmetry restoration, are evaluated by using the momenta of the mass spectra of vector mesons [5–7]. Thus, it is crucial to measure the mass spectra of vector mesons in a different environment, and conversely, when modifications of mass spectra are observed in the matter, it suggests the partial restoration of the chiral symmetry in such an environment. Several experimental efforts are performed to measure mass modifications of vector mesons in a finite temperature and/or density matter.

At first, measurements in high energy heavy ion collisions were performed, since the chiral symmetry restoration is one of the good signatures for the creation of quark–gluon plasma in the high-temperature region. Measurements were carried out at the Super Proton Synchrotron (SPS) [8], Relativistic Heavy Ion Collider (RHIC) [9, 10], and Large Hadron Collider (LHC) [11]. All experiments showed modifications of mass spectra in a mass region of a $\rho$ meson. It was difficult to extract information on the chiral order parameters, since the created matter had a time evolution in a collision and the obtained spectrum was an integration of all stages of the collision.

## 2. Vector mesons in a nucleus

Measurements of vector mesons in a nucleus, as a finite density matter, were also performed by several experimental groups. It is theoretically predicted that quark anti-quark condensates are linearly decreased with the increasing baryon density [3]. Thus, significant modifications of vector meson mass can be expected even in a nucleus. Also, a nucleus is a stable object, and one can ignore the time evaluation of the collision, which is an issue in the case of heavy ion collisions.

An experiment was performed at KEK-PS (proton synchrotron) to measure mass spectra of vector mesons in proton-nucleus reactions [12, 13]. Vector mesons were identified by electron–positron decay modes, and carbon and copper targets were used. Mass modifications of $\rho$, $\omega$, and $\phi$ mesons were observed. The results were interpreted as a mass reduction of the vector mesons, and it was evaluated that the $\rho$, $\omega$ mesons, and the $\phi$ meson had 9% and 3% of mass reduction with respect to the normal nuclear density, respectively.

The HADES experiment at GSI measured mass spectra of $\rho$ mesons in proton–nucleus and nucleus–nucleus reactions using electron–positron decay modes [14]. The obtained mass spectra showed an enhancement in the low mass region which can be understood as mass modifications of $\rho$ mesons.

Other measurements were done using $\gamma$ induced reactions. The CLAS experiment at J-Lab measured the mass spectra of $\rho$ mesons using electron–positron decay modes [15]. The results show modifications of mass distribution of the $\rho$ meson, however, they do not show a mass reduction of the $\rho$ meson. The CBELSA/TAPS experiment measured yields of $\omega$ mesons production in $\gamma$A reactions [16]. The result shows a large broadening of $\omega$ meson mass width. It seems that these results contradict the KEK results, however, the used reactions were different, and such differences can cause different results. Further information is necessary to understand the experimental situation.

## 3. J-PARC E16 experiment

We are carrying out a new experiment to measure the mass spectra of vector mesons in nuclei at the Japan Proton Accelerator Research Complex (J-PARC) [17]. The experiment is called the J-PARC E16 experiment and is a successor of the experiment at KEK-PS. The experiment aims to have systematic studies with two orders of magnitude larger statistics than that of the KEK experiment.

In the experiment, we measure electron–positron decays of vector mesons in proton-nucleus collisions. To measure the mass spectra of the vector mesons precisely, final state interactions between medium and daughter particles should be minimized as much as possible, and for this reason, electron–positron decays are chosen. Although

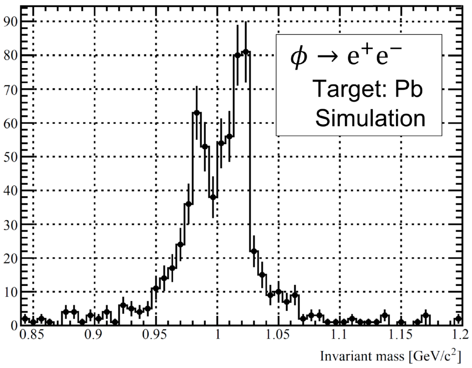


Fig. 1. Expected invariant mass spectrum of $\phi \to e^+e^-$ for lead target and $\beta\gamma$ of $\phi$ less than 0.5 obtained using a Monte Carlo simulation including full detector simulations assuming a mass shift of 9%.

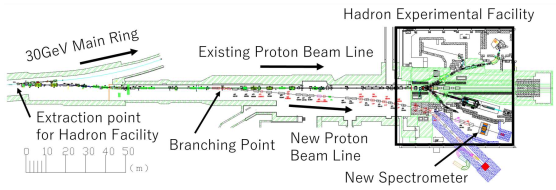


Fig. 2. Schematic view of Hadron Experimental Facility and a transfer beam line.

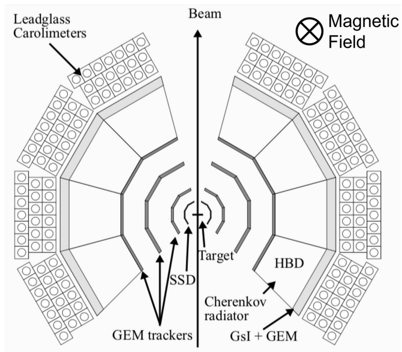


Fig. 3. Schematic view of the spectrometer.

a hadronic decay of vector mesons, such as $\phi \to K^+K^-$, has a large branching ratio and can obtain large statistics easily, distortions of the mass spectra in hadronic decays are too large to study mass modifications of the vector mesons due to final state interactions of decayed hadrons.

In this experiment, a high-intensity beam is required to obtain enough statistics, because electron–positron decays of vector mesons have a very small branching ratio ($\sim 10^{-4}$), and a very thin nuclear target ($\sim$ 0.2% interaction length) must be used to minimize radiation tails of mass distributions. For the current experiment, the intensity of the proton beam is $1.0 \times 10^{10}$ per spill (2 s duration, 5.2 s cycle). Detectors need to cope with a maximum interaction rate of 10 MHz. This is also challenging. Several nucleus targets, such as carbon, copper, lead, and $CH_2$, are used to figure out experimental effects and evaluate nuclear size dependence.

An expected invariant mass spectrum of electron–positron pairs is shown in Fig. 1. The spectrum is obtained using a Monte Carlo simulation, including full detector simulations. A mass shift of 9%, which is obtained in the KEK-PS experiment, is assumed, and only very slowly moving $\phi$ mesons ($\beta\gamma < 0.5$) are selected. One can expect that half of the generated $\phi$ mesons decay inside a nucleus. The mass spectrum shows two peaks. One peak has an intrinsic mass position, which is generated by $\phi$ mesons decayed in free space. The other peak consists of $\phi$ mesons decayed inside nuclei.

### 3.1. Beam line and spectrometer

A new beam line and a new dedicated spectrometer were constructed at the J-PARC Hadron Experimental Facility. The new beam line was built as a branch of the existing beam line, as shown in Fig. 2.

There is a branching point in the middle of the existing transfer beam line from an accelerator to the Hadron Experimental Facility. At the branching point, a very small fraction of the beam ($\sim$ 0.1%) is separated and transferred to a new beam line and used for the experiment. Since the proton beam is directly transferred from the accelerator, the condition of the proton beam strongly depends on the optics of beam transportation and the status of the accelerator. Thus, the conditions and properties of the proton beam were carefully studied during beam commissioning in 2020 and 2021. As a result of the commissioning, the beam optics were improved to suppress background events due to event overlaps.

Figure 3 shows a horizontal cross-section of the spectrometer at the height of the beam line. Detectors are placed in a magnetic field, and the direction of the magnetic field is perpendicular to the horizontal plane. The beam is horizontally transported at the center of the spectrometer. The spectrometer is located closer to the downstream of the beam. Three targets are placed at the center of the spectrometer and irradiated simultaneously. For the pilot run and the first physics run, two copper targets and one carbon target are used to compare the results directly to those of the KEK-PS experiment. The spectrometer consists of four layers of tracking detectors and two kinds of electron identification counters. Tracking detectors are one layer of a Silicon Strip Detector (SSD) and three layers of Gas Electron Multiplier (GEM) trackers [18]. For electron identifications, a GEM-based gas Čerenkov counter, a so-called Hadron Blind Detector (HBD) [19], and a Lead Glass detector (LG) are used. The spectrometer has a total of 26 modules, and each module has these detector components. The spectrometer is divided into three parts vertically — the top and bottom parts contain 9 modules each, and the middle part contains 8 modules. For the pilot run and the first physics run, only the middle part is utilized due to a limited budget.

The SSD has the same sensor as the ATLAS experiment used [20]. The sensor has a sensitive area of $61 \times 62$ mm$^2$ and single-sided read-out strips. The pitch of read-out strips is 80 $\mu$m. The sensor is being replaced by new sensors developed by the FAIR-CBM experiment [21]. The new sensor has a similar sensitive area ($60 \times 60$ mm$^2$) to the ATLAS sensor and double-sided read-out strips. The pitch of read-out strips is 50 $\mu$m. Improved resolutions of position measurements and additional information for a $y$ direction will be expected.

The GEM tracker is used as the main tracking device, since the amount of detector material must be small to have a good momentum resolution of electron–positron measurements in a low-momentum region. Also, the counting rate of the experiment is high (5 kHz/mm$^2$), and the GEM tracker has a high rate capability. The GEM tracker is a kind of Micro-Pattern Gas Chamber (MPGC), and the gas of Ar–$CO_2$ (70%–30% mixture) is used. The GEM tracker consists of three GEM foils and one read-out foil. A drift gap of 3 mm is set at the top of the GEM foils. When charged particles go through the gas in the drift gap, ionized electrons are generated. Ionized electrons are multiplied in a high electrical field of the GEM foils and transferred to the read-out foil. The read-out foil has two-dimensional strips, and the pitches of the $x$ and $y$ directions are 400 $\mu$m and 1.4 mm, respectively. A prototype of the GEM tracker was tested and achieved position resolution of the prototype was less than 100 $\mu$m [22], which satisfies the requirements of the experiment.

The HBD is a gas Čerenkov counter with a window and mirrorless configuration to cover a large acceptance for electron identification [23]. The HBD consists of a gas radiator and a photo-detection detector. The gas of $CF_4$ is used for the radiator. The GEM detector is also used as the photo-detection detector. Cesium iodide is evaporated on the top of the GEM foil as a photocathode. Čerenkov lights generate photoelectrons on the photocathode and photoelectrons, are multiplied by GEM foils and transferred to a read-out plane. The read-out plane has hexagonal pads, and the size of the pad is 10 mm. The pad size is small compared to the blab size of the Čerenkov light (34 mm $\phi$). One electron usually produces multiple hits, though a $\pi$ meson has only one hit. The number of hit pads helps to suppress background hits by $\pi$ mesons. A prototype of the HBD showed a $\pi$ meson rejection power of 99.4% with an electron efficiency of 63%.

The LG is an additional electron-identification detector using an electromagnetic shower. The LG consists of a crystal and a photomultiplier. The crystal is SF6W and was used for the KEK-TOPAZ experiment [24]. The size of the crystal has been modified for our experiment, and the thickness of the crystal is eight radiation lengths. The thickness is relatively small, however it is optimized to have the best separation of electrons and $\pi$ mesons in a momentum range of the current experiment. The detectors are located in the magnetic field, and fine-mesh photomultiplier tubes (PMTs) (Hamamatsu R6683) are used. A prototype of the LG was tested, and a $\pi$ meson rejection power of 92% was achieved with an electron efficiency of 90%.

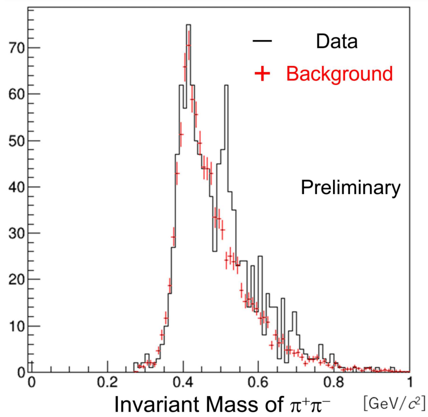


Fig. 4. Invariant mass distribution of $\pi^+\pi^-$.

### 3.2. Results of pilot runs

Constructions of a beam line and detectors were started in 2012. The first beam was extracted in June 2020. Beam studies and detector shake-down were performed in 2021 and 2022. Pilot run data were collected to evaluate detector performances.

A momentum reconstruction process was checked with the pilot run data. Tracks of charged particles in a magnetic field were reconstructed using the information of the SSD and the GEM trackers. The magnetic field of the spectrometer was measured before starting the experiment. The momenta of the charged particles are evaluated using a Runge–Kutta method.

The invariant mass distribution of $\pi^+\pi^-$ pairs, calculated using the reconstructed momenta, is shown in Fig. 4. The background of the spectra was produced by non-correlated $\pi^+\pi^-$ pairs and evaluated by an event-mixing method. The evaluated background reproduced well the background of the data. A peak is observed at the mass of around 0.5 GeV/$c^2$, and it corresponds to decays of $K_S$ mesons. The expected mass center position and width of $K_S$ mesons are evaluated using the full detector simulations assuming a known lifetime and momentum distribution of $K_S$. The obtained results are consistent with simulation results. Thus, the momentum reconstruction succeeded for the pilot run.

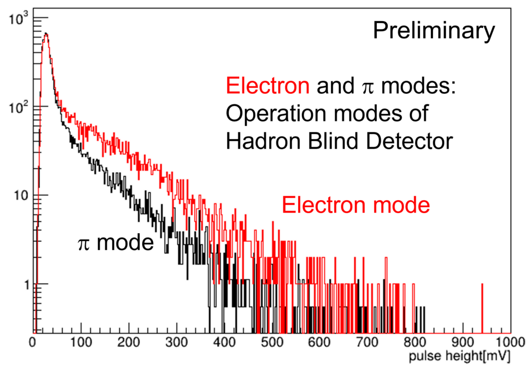


Fig. 5. Pulse height distributions of Lead Glass Calorimeter for electron candidates and $\pi$ meson candidates.

Performances of electron identification detectors were also examined with the pilot run data [25]. Electron candidates were identified by the number of photoelectrons and the number of hit pads of an HBD cluster and the pulse height of the LG.

Distributions of the LG pulse height are shown in Fig. 5. The HBD has two operation modes, a so-called electron mode, and a $\pi$ mode. The HBD was operated to select electron and $\pi$ meson candidates for the electron and $\pi$ mode, respectively. Distributions in the figure correspond to these two modes. A clear enhancement for the electron mode is seen in a large pulse height region, as expected. There are contaminations of $\pi$ mesons in the distribution for the electron mode due to misidentifications of the HBD and it makes a peak in a low pulse height region.

## 4. Future prospects

The first physics data taking period is planned for 2023. The middle part of the spectrometer will be installed, and the accumulation of $1.5\times10^4\phi$ mesons is expected for the first physics run. The spectrometer will be upgraded to cover a full acceptance after the first physics run, and 100 times larger statistics than that of the KEK-PS experiment are finally expected [17].

Measurements of $K^+K^-$ decays of $\phi$ mesons are also planned to have further information on mass modifications of $\phi$ mesons and also K mesons. A proposal was already submitted to the Program Advisory Committee of J-PARC, and physics importance has been recognized by the committee. New detectors for $K$ meson identifications are needed, and development of the detectors is underway.

To study the properties of a higher-density matter, experiments with heavy ion collision are also discussed at J-PARC. An energy range of a heavy ion beam at J-PARC is suitable for generating high-density matter. An achieved baryon density will be 7–8 times larger than the normal nuclear matter density. Especially, measurements of di-leptons are missing in this energy region, and they have been awaited for a long time.

## 5. Conclusions

An experiment to measure mass spectra of vector mesons in nuclei is being carried out at J-PARC in Japan to study the origin of hadron mass and the partial restoration of chiral symmetry of quantum chromodynamics in a finite density matter.

A new beam line was built to provide a high-intensity proton beam for the experiment, and the beam commissioning was started in 2020. A new spectrometer was also built to measure the mass spectra. Performances of the detectors were evaluated using the pilot run data, which were taken in 2020 and 2021, and the obtained performances satisfied requirements.

The physics data taking will start in 2023. Further studies are also planned.

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