

## $\Omega$ baryon spectroscopy with negative kaon beam at J-PARC

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Hadrons are composite particles of quarks and gluons interacting with each other. One of the fundamental goals of hadron physics is to understand the formation of hadrons. Hadron physics research programs at the J-PARC hadron experimental facility aim to reveal the structure of hadrons using the world's most intense meson beams. The high-intensity and high-momentum negative kaon beam provides unique opportunities to investigate the structure of hadrons, with the  $\Omega$  baryon playing an important role. We plan a spectroscopic investigation of the  $\Omega$  baryon at J-PARC. A high-momentum unseparated beam line, called  $\pi 20$ , is under construction, and a dedicated high-momentum beam line, called K10, is also planned as part of the extension project for the hadron experimental facility. We will conduct systematic studies of  $\Omega$  baryons using an intense  $K^-$  beam at J-PARC.

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## 1. Introduction

Hadron consists of quarks that interact with gluons. Due to the non-perturbative nature of quantum chromodynamics (QCD), hadrons are considered to be formed through the complex, non-trivial dynamics of quantum fields. Lattice QCD has made crucial contributions to establishing that QCD is indeed the theory of the strong interaction for hadrons. However, the question, “how quarks build hadrons” remains unresolved. The dynamics of low-energy QCD, such as the formation of hadrons, have not been clearly explained yet. We use a quark model to understand the properties of hadrons. While the properties of the ground state, such as mass and magnetic moment, are well understood, the internal structures of excited states are not well described or clarified by the ordinary quark model. These excited states form as hadronic molecules or multi-quark states, known as exotic hadrons [1]. In order to understand the rich internal structure of hadrons, it is necessary to study the dynamics of the non-trivial QCD vacuum in the low-energy regime. Our goal is to study the non-trivial dynamics of QCD in baryon structure through spectroscopy studies of baryons at J-PARC. Spectroscopy of the  $\Omega$  baryon is expected to provide a unique opportunity to achieve this goal.

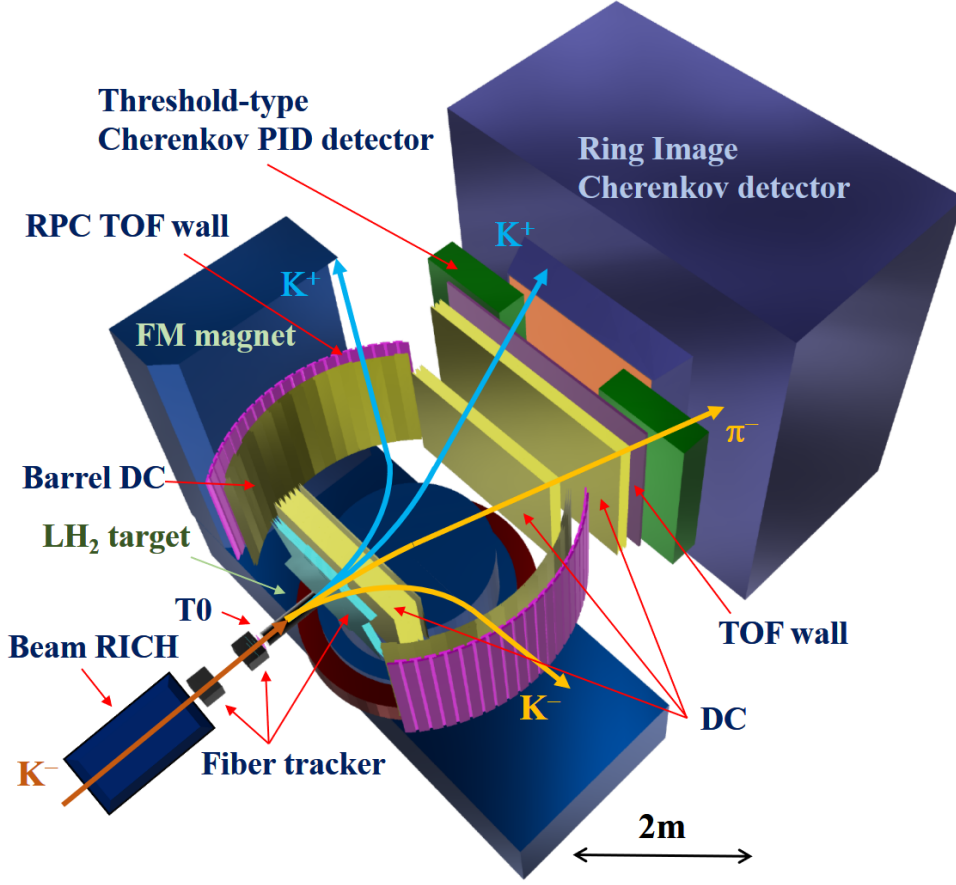
## 2. High-momentum secondary beam lines and MARQ spectrometer

### 2.1 $\pi 20$ and K10 beam lines

We have proposed a systematic approach to baryon spectroscopy [2–4] in order to understand the dynamics of the non-trivial QCD vacuum in the structure of baryons at the J-PARC hadron experimental facility. The high-momentum beam line, which provides high-intensity unseparated hadron beams of up to 20 GeV/c, called  $\pi 20$ , is under construction. As part of the hadron experimental facility extension project [5], we also plan to construct a high-momentum beam line to provide high-purity  $K^-$  beam of up to 10 GeV/c. Intense  $K^-$  beam provided by both the  $\pi 20$  and K10 beam lines are essential for spectroscopic investigations of the  $\Omega$  baryon. A general-purpose spectrometer system called MARQ is under construction at  $\pi 20$ , and a similar dipole spectrometer system will be constructed at K10.

### 2.2 MARQ Spectrometer

Figure 1 shows a schematic view of the MARQ (Multipurpose Analyzer for Resonance and Quark dynamics in hadrons and hadronic systems) spectrometer [5]. The MARQ spectrometer satisfies the requirements of all the planned spectroscopy experiments at  $\pi 20$ . It consists of a large dipole magnet, tracking detectors, time-of-flight detectors and particle identification detectors. Some of the tracking and time-of-flight detectors are placed inside the magnet’s gap. The liquid hydrogen target is positioned in front of the dipole magnet’s entrance. We have adopted a triggerless streaming-readout data acquisition system [6]. The MARQ spectrometer will be constructed as a new platform for hadron physics at J-PARC.

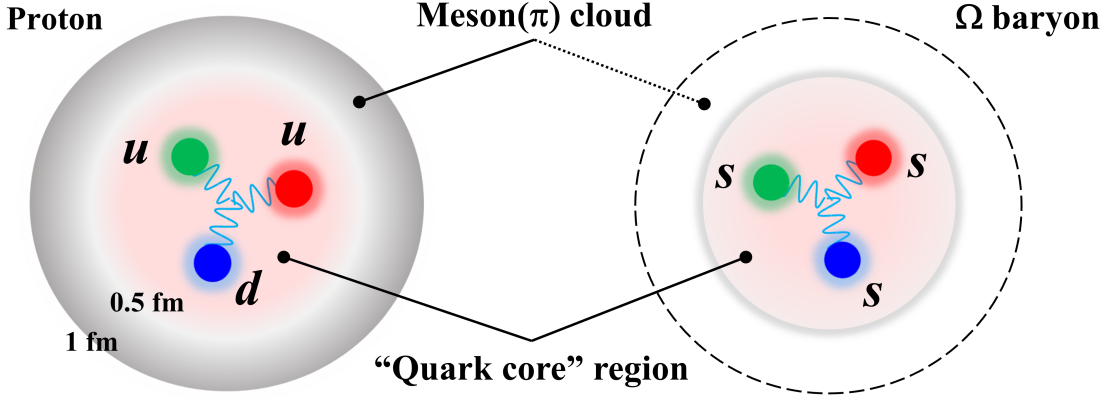


**Figure 1:** Schematic view of the MARQ spectrometer to be constructed at  $\pi 20$ .

### 3. $\Omega$ baryon spectroscopy

The  $\Omega$  baryon is assigned as a member of the decuplet representation in the SU(3) flavor symmetry group. However, the SU(3) symmetry is broken by the mass of the  $s$  quark, which is heavier than the nearly equal masses of the  $u$  and  $d$  quarks. The pattern of SU(3) symmetry breaking could be used to predict the mass of the  $\Omega$  baryon under the assumption of equal mass spacing between the decuplet members. Broken SU(3) also leads to the apparent mass difference between the pion ( $m_\pi \sim 140$  MeV) and the kaon ( $m_K \sim 500$  MeV). This difference, together with the single-flavor nature, gives the  $\Omega$  baryon their unique properties. In addition, as shown in Fig. 2, without the meson (pion) cloud present in the light baryon structure, we may be able to directly access the “quark core” region of the baryons. Furthermore, we can expect the  $\Omega$  baryon to be smaller in size than the light-flavored baryons, which are surrounded by a meson (pion) cloud.

We propose an experiment to study  $\Omega$  baryons at the J-PARC hadron experimental facility [4]. Our aim is to investigate the masses and decays of excited  $\Omega$  baryons ( $\Omega^*$ s) in the  $K^- p \rightarrow \Omega^{*0} K^+ K^{*0}$  reaction at incident kaon momenta ranging from 7 to 10 GeV/ $c$ . Spectroscopy of the  $\Omega^*$ 's is a unique testing ground for revealing diquark correlations by comparing with other sectors such as  $\Lambda_c^*$  and  $\Xi^*$  since neither diquark correlations nor a pion cloud are expected in an  $\Omega^*$  system. The mass of a produced  $\Omega^*$  including the ground state  $\Omega$  ( $\Omega^{(*)}$ ) can be determined using a missing-mass technique

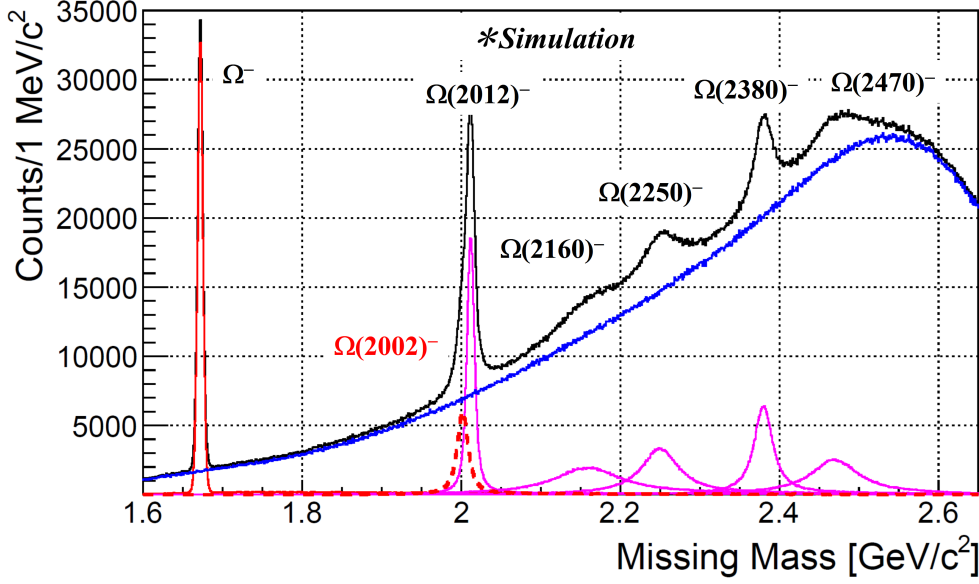


**Figure 2:** Schematic illustration of the internal structure of proton and  $\Omega$  baryon.  $\Omega$  baryon is free of the pion cloud effect due to the suppression of the single pion coupling.

with the four-momenta of the initial-state  $K^-p$  and final-state  $K^+K^+\pi^-$  in the  $K^-p \rightarrow \Omega^{(*)-}K^+K^{*0}$  reaction. In this case, the selected events are those in which the  $K^+\pi^-$  invariant mass corresponds to the  $K^{*0}$  mass. The missing system  $p(K^-, K^+K^{*0})$  gives  $S = -3$ , which eliminates a large amount of background from  $\Sigma^*$ -produced events.

Figure 3 shows the expected mass spectrum of the  $\Omega^{(*)}$  baryon, including the background contribution, for an incident kaon momentum of 8 GeV/c. We measure the masses, widths, and decays of excited  $\Omega$  baryons with excitation energies of up to 1 GeV. The background contribution is estimated using the JAM code [7]. The mass of the  $\Omega^{(*)-}$  is calculated using the missing mass of the  $p(K^-, K^+K^{*0})$  and the cross section of  $K^-p \rightarrow \Omega^{(*)-}K^+K^{*0}$  for each  $\Omega^{(*)-}$  is assumed to be 63 nb. The number of events for each peak is approximately  $\sim 3.3 \times 10^5$ , which can be obtained in 100 days of beam time at K10. As the number of events is large, the precision of the mass determination in this spectrum is better than 1 MeV, depending on the width of the corresponding  $\Omega^{(*)-}$ . In order to achieve accurate mass determination, the absolute momentum scale in the spectrometer must be calibrated carefully. Various peaks corresponding to hyperons and other baryons can be used in similar mass spectra. Thus, the accuracy would also be better than 1 MeV after calibration. Conversely, it is difficult to accurately determine the width of an  $\Omega^{(*)-}$ . The observed peak is smeared by the experimental mass resolution of 2.5–4.5 MeV( $\sigma$ ). The peak may differ in shape from the Breit-Wigner function due to overlap with other peaks and background processes, including interference effects. The accuracy of the width determination expected is better than 1 MeV for an isolated Breit-Wigner peak with a width of several 10 MeV. We expect the accuracy of the width determination is better than a few MeV for high-mass  $\Omega^*$ s, which are overlapped with other contributions.

In Fig. 3,  $\Omega(2002)^-(1/2^-)$  is also shown as the  $LS$  partner of  $\Omega(2012)^-(3/2^-)$  with an assumed mass of 2.002 GeV and width of 12 MeV (twice the  $\Omega(2012)^-$  width). The production cross section of the  $\Omega(2002)^-$  is assumed to be half that of the  $\Omega(2012)^-$ . Although the peak of the  $\Omega(2002)^-$  is not clearly visible in the expected mass spectrum, its contribution appears as a distortion of the  $\Omega(2012)^-$  peak in the lower tail region. By analysing the asymmetric  $\Omega(2012)^-$  peak structure, we



**Figure 3:** The expected mass spectrum of the  $\Omega^{(*)-}$ , including background contributions, is shown for an incident kaon momentum of 8 GeV/c over a beam time of 100 days at K10. This spectrum was obtained using the missing mass of the generated events produced by the  $p(K^-, K^+K^{*0})$ . The smooth blue curve represents the background contribution estimated by JAM. The contributions from the ground state of the  $\Omega^-$  and  $\Omega^{*-}$ 's are also plotted in red and magenta, respectively.

can determine the mass and width of  $\Omega(2002)^-$ , even if its  $LS$  partner has the same mass as  $\Omega(2012)^-$  but a different width. High-statistic data would enable us to reveal the  $LS$  partner of the  $\Omega(2012)^-$ . Information on the energy splitting between the  $1/2^-$  and  $3/2^-$  states of the  $\Omega$  baryon allows us to study the origin of the level splitting due to the spin-orbital force.

As for a possible candidate of the Roper-like resonance, the  $\Omega^*$ ,  $\Omega(2160)^-(3/2^+)$ , which has a broad width of around 100 MeV and an excited energy of around 500 MeV, the corresponding events using these properties in the simulation are distributed over a wide range and only form a shoulder in Fig. 3. A peak or bump would be clearly observed corresponding to each of the other  $\Omega^{*}$ 's with narrower widths. The mass and width of the Roper-like state of the  $\Omega$  with the expected spin and parity of  $3/2^+$  can be measured. From the mass measurement, we can confirm whether the mass appears at the expected position from systematics in corresponding states with different flavor contents. The decay width of the Roper-like state of the  $\Omega$  with an expected spin and parity of  $3/2^+$  can be related to the mean square of the internal quark motion ( $\langle p_q^2 \rangle$ ) as described in [8] so that we can extract the mean squared size from the relation of  $\langle r_q^2 \rangle \sim 1/\langle p_q^2 \rangle$ . As we expect the  $\Omega$  baryon to be free of the meson (pion) cloud effect due to the suppression of single-pion coupling, the measured decay width provides an indication of the size of the “quark core” of the  $\Omega(2160)^-(3/2^+)$  state.

## 4. Summary

One of the fundamental goals of hadron physics is to understand how quarks build hadrons. In order to understand the hadron formation, it is necessary to study the dynamics of the non-trivial QCD vacuum in the low-energy regime. The  $\Omega$  baryon, which has a single flavor system, plays an essential role in this investigation because of its simple structure and freedom from the pion cloud. The  $\Omega$  baryon enables us to study the quark core region of the baryon structure, helping us to understand spin-dependent forces and the motion of the internal quarks. We plan to conduct systematic measurements of the excited states of  $\Omega$  baryons at J-PARC  $\pi 20$  and K10 beam lines using high-intensity and high-momentum  $K^-$  beam with the MARQ spectrometer. A spectroscopic study of the  $\Omega$  baryon can provide unique information for understanding the dynamics of the non-trivial QCD vacuum.

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