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Search for the H-dibaryon near $\Lambda\Lambda$ and $\Xi^- p$ thresholds at J-PARC

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A recent claim from the LHCb collaboration on the observation of two hidden-charm pentaquark states revives hopes for experimental discoveries of other multiquark baryonic states such as the H-dibaryon with a 6-quark (*uuddss*) configuration. Recent theoretical predictions for the mass of H-dibaryon pointing to the mass region near the $\Lambda\Lambda$ threshold also encourage experimental searches. We have proposed a dedicated experiment to search for the H-dibaryon in the bound and unbound mass regions near $\Lambda\Lambda$ threshold. We plan to measure production of $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ systems in the $^{12}C(K^-, K^+)$ reaction at J-PARC. We are now constructing a large-acceptance hyperon spectrometer consisting of a superconducting dipole magnet and a time projection chamber, which allows conclusive experimental searches with a precise 1-MeV mass resolution.

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1. Introduction

The existence of multiquark hadrons is now firmly established in the meson sector since the Belle Collaboration has shown proof for several tetraquark states. Recently, the LHCb collaboration claims the observation of two hidden-charm pentaquark states. The proof supports new experimental efforts for discoveries of more exotic baryonic states such as the H-dibaryon with a 6-quark (*uuddss*) configuration ($I = J = 0$) of maximal spatial symmetry [1]. The discovery of the H-dibaryon would also provide crucial information on the ΛΛ interaction.

Recent Lattice QCD calculations have had great success in reproducing the properties of the nucleon-nucleon interaction [2]. The HAL collaboration extended this Lattice QCD calculation to the baryon-baryon interactions [3]. Very recently, they reported preliminary results on $^1S_0$ phase shifts in $I = 0$ ΛΛ and $N\Xi$ channels at $m_\pi = 145$ MeV [4], which indicate a sharp resonance state between ΛΛ and $\Xi^- p$ thresholds.

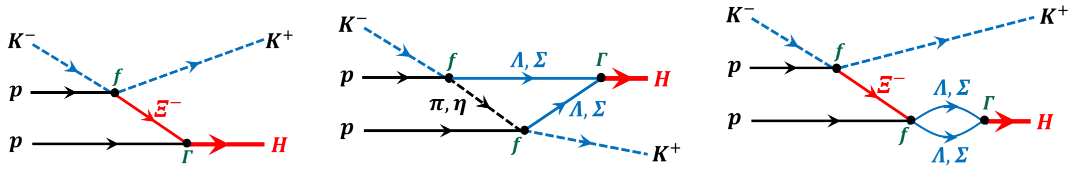
While experimental searches for an unbound H-dibaryon have yielded no conclusive evidence in high-energy experiments, a KEK experiment (E224) has reported enhanced ΛΛ production near the ΛΛ threshold in the ^{12}C(K^-,K^+) reaction with a scintillating-fiber active target [5], which was reconfirmed in a later KEK experiment (E522) with a larger target volume [6]. The enhancement can then be interpreted as either the possible existence of an H-dibaryon resonance with the mass of 2242 MeV$/c^2$, just 12 MeV$/c^2$ above the threshold, or a strongly-attractive ΛΛ final-state interaction, or both.

In the (K^-,K^+) reaction, the lowest-order process for H production on a diproton pair can be written as [7, 8]: $K^- + (pp) \to K^+ + (\Xi^- p) \to K^+ + \mathrm{H}$, where pp and $\Xi^- p$ pairs should be in a relative $^1S_0$ state, in order to form the $J^\pi = 0^+$ H-dibaryon, as shown in Fig. 1(a). In the second-order processes, the H can be formed from ΛΛ/ΛΣ/ΣΣ fusion, each produced via intermediate meson-induced processes (in Fig. 1(b)) or Ξ^--induced processes (in Fig. 1(c)). The decay vertex amplitude Γ describes the fusion of $\Xi^- p$ systems into a six quark state H of radius R of harmonic oscillator wave functions for the quarks: $\Gamma \propto \exp\left[-\frac{R}{12}(\vec{p}_p - \vec{p}_\Xi)\right]^2$, which depends only on the relative momentum between Ξ^- and p. The momentum transfer $q \geq 366$ MeV$/c$ (at $p_{K^-} = 1.8$ GeV$/c$) always remains larger than the Fermi momentum $p_F = 250$ MeV$/c$. However, nuclear Fermi motion enables us to reach the kinematic region where the relative momentum is fairly small [8]. The forward ΛΛ production cross section for the ^{12}C(K^-,K^+) reaction was measured to be 7.6 μb$/$sr [5], which indicates a sizable production for the first-step process in the two second-order diagrams, as shown in Fig. 1(b) and 1(c).

2. J-PARC E42 Experiment

The J-PARC E42 experiment aims at searching for the H-dibaryon in the mass region near ΛΛ threshold via the ^{12}C(K^-,K^+) reaction at $p_{K^-} = 1.8$ GeV$/c^2$. The primary goal of the proposed experiment is to unveil the origin of the enhanced ΛΛ production near threshold [5, 6]. The proposed experiment has two orders of magnitude higher sensitivity than the previous KEK-PS experiments because of higher K^- beam intensity and much less secondary interaction in a time projection chamber. We are also able to explore information on the scattering length of ΛΛ interaction in the proposed experiment.

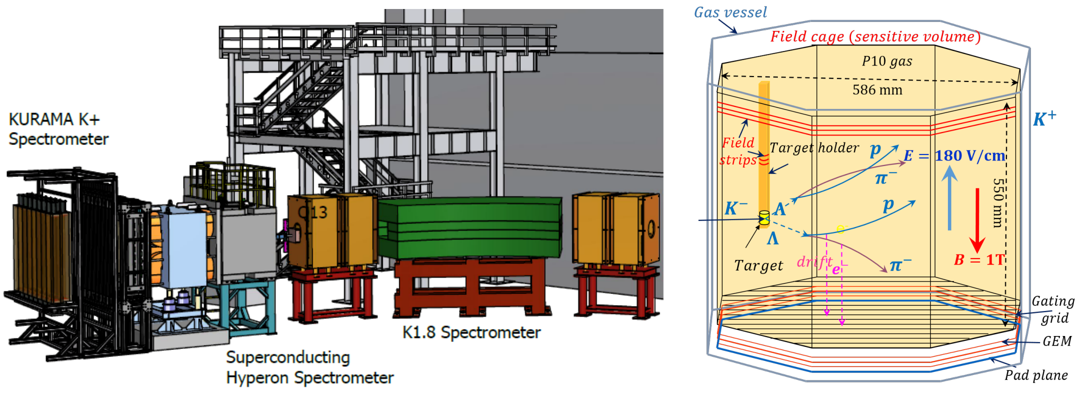
PoS(Hadron2017)124



(a) (b) (c)

Figure 1: (a) Lowest-order process for H-formation via $\Xi^- p$ fusion in the (K^-, K^+) reaction. f indicates scattering amplitude and Γ represents the decay vertex amplitude. (b) Two-step process for H-formation via intermediate meson-induced processes for $S = -1$ hyperon production following associated hyperon production in the $K^- p$ reaction. (c) Second-order process for H-formation from the $\Lambda\Lambda \to$ H.

The heart of the experiment is a time projection chamber as a central tracking device in a superconducting dipole magnet. This new Hyperon Spectrometer has a large acceptance with the Helmholtz-type configuration. The time projection chamber (HypTPC) provides a good tracking capability for decay particles from the H-dibaryon such as $\Lambda p \pi^-$, $\Lambda\Lambda$, and $\Xi^- p$. Beam particles are identified with Cherenkov detectors and time-of-flight measurement in the K1.8 beam spectrometer at Hadron Hall, J-PARC. Outgoing K^+ particles are tagged by the forward KURAMA spectrometer consisting of a 0.7-T dipole magnet, trigger hodoscopes, drift chambers and a time-of-flight detector, as shown in Fig. 2(a).



(a) (b)

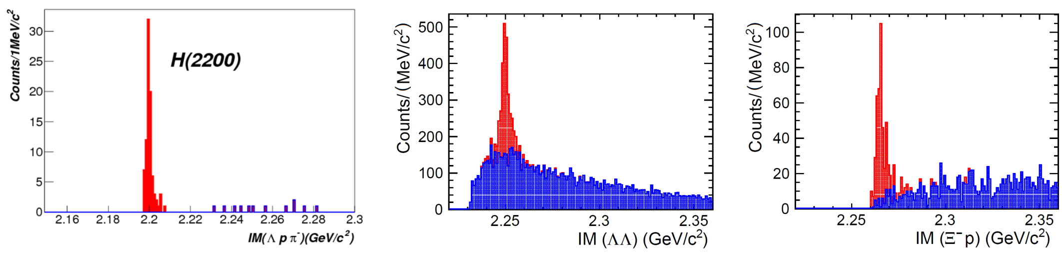
Figure 2: (a) Schematic view of the E42 experimental setup at K1.8 beamline. The Hyperon Spectrometer consisting of a time projection chamber (HypTPC) in the superconducting dipole magnet will be placed between the K1.8 beam spectrometer and the forward KURAMA spectrometer. (b) Layout of the HypTPC.

The superconducting dipole magnet was designed to have a magnetic field uniformity of $B_r/B_y < 1\%$ over the TPC drift volume of $r = 250$ mm. The main magnetic field (B_y) is aligned along the vertical direction, such that the beam passes through a lateral surface of the cylindrical magnet volume. To accommodate the TPC and the surrounding trigger scintillators, the inner radius of the magnet was designed to be $r = 400$ mm [9]. A pair of concentric coils are separated from each other by the same distance to the coil radius of $r = 500$ mm. The operation current for this experiment is 75 A for the central magnetic field of 1.0 T.

The design challenges of the Hyperon Time Projection Chamber (HypTPC) can be emphasized on the two aspects; the geometrical layout and the amplification structure to achieve excellent momentum and spatial resolutions with large acceptance. To meet the design goals, the octagonal prism layout and the triple GEM (Gas Electron Multiplier) amplification were chosen. Beam particles pass perpendicular to the TPC drift axis, and a solid target is installed inside the TPC drift volume. A readout plane is placed in the bottom end of the HypTPC volume, each consisting of a gating grid, a triple GEM layer and a concentric anode pad plane, as shown in Fig. 2(b). The gating-wire grid and GEM layers provide high-rate capability at an event rate of up to 10^6 Hz with a good suppression of the ion backflow.

The HypTPC field cage is housed in an outer gas vessel, consisting of the cathode plane, the field strips, field wire planes for laser calibration and the target holder positioned 143 mm upstream from the TPC axis. The whole volume of the octagonal field cage is filled with a gas mixture of Ar-CH_4 (P10). It has an overall drift length of 550 mm in the vertical direction. The field cage is operated at a drift field of 180 V/cm with a high voltage of -12.4 kV at the octagonal cathode plane. The readout chamber consists of a top gating wire plane, a middle triple-GEM layer and a bottom pad plane. Top two GEM sheets are 50 μm thick and the bottom one is 100 μm thick. The readout pad configuration has been optimized for spatial resolution to be 0.2-0.3 mm at the gas gain of 10^4 [10].

The estimate of the $\Lambda\Lambda$ event yield has been performed with the following conditions. The K^- beam intensity is assumed to be 6×10^5 in 5.5 s (spill interval). The acceptance of the K^+ spectrometer is estimated to have a solid angle of 0.16 sr. The K^+ detection efficiency is assumed to be 0.5, taking the in-flight K^+ decay probability into account. Our estimate of the $\Lambda\Lambda$ production cross section is based on the KEK-PS E224 results (7.6 μb/sr) [5]. As a result, we expect to detect 1.5×10^4 $\Lambda\Lambda$ events in 30-day physics runs, which is more than two orders of magnitude higher statistics than those observed in two previous KEK experiments. The simulated $\Lambda\Lambda$ invariant-mass spectrum with the H(2250) events is shown in Fig.3(b), assuming the production cross section of 1.0 μb/sr. The H-dibaryon peak structure can still be identified with the intrinsic decay width up to $\Gamma_{\rm H} = 5$ MeV.



(a) (b) (c)

Figure 3: (a) Reconstructed masses for the H(2200) $\to \Lambda p\pi^-$ decay events assuming the production cross section of 0.2 μb/sr. (b) Reconstructed $\Lambda\Lambda$ mass spectra with the 2.250-GeV/c^2 H-dibaryon events assuming the production cross section of 1.0 μb/sr. (c) Reconstructed masses for the H(2265) $\to \Xi^- p$ decay events assuming the production cross section of 0.3 μb/sr.

For the H $\to \Lambda p\pi^-$ decay, candidate events should have two V tracks detected and one of them should be a Λ which originate from the other. We impose a constraint that the H decay vertex should be out of the target volume. Therefore, there is no background process misidentified as the H $\to \Lambda p\pi^-$. Fig. 3(a) shows a reconstructed $\Lambda p\pi^-$ mass spectrum with weakly-bound H-dibaryon events at 2.200 GeV$/c^2$ assuming 0.2 μb/sr for H-dibaryon production cross-section. The branching ratio for the H $\to \Lambda p\pi^-$ decay channel is taken as 25%. The $\Xi^- p$ invariant mass spectrum is also shown in Figure 3(c) with the H mass at 2.265 GeV$/c^2$.

The J-PARC E42 experiment is sensitive to a few tens of nb/sr for the H $\to \Lambda\Lambda$ decay. For the bound H-dibaryon decaying to $\Lambda p\pi^-$, it is sensitive up to a few nb/sr, which is two orders of magnitude smaller than the current level of upper limits on H-dibaryon production in the mass range from $\Lambda p\pi^-$ to $\Lambda\Lambda$.

3. Summary

The E42 experiment aims at the H-dibaryon search in the mass region near $\Lambda\Lambda$ threshold via the ^{12}C(K^-,K^+) reaction at J-PARC. Hyperon-nucleon interaction, particularly in $S=-2$ system, can also be explored. The large-acceptance Hyperon spectrometer will also be utilized for extensive studies of baryon resonances in $\pi p \to \pi\pi N$ reactions (J-PARC E45) [11] and for studying a narrow Λ^* resonance in $K^- p \to \Lambda\eta$ reaction (J-PARC P72).

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