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Letter of Intent for 50 GeV Proton Synchrotron

Search for H-Dibaryon with a Large Acceptance Hyperon Spectrometer

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Abstract

Recent Lattice QCD calculation, which succeeded to reproduce nucleon-nucleon potential, has been extended to baryon-baryon interactions in $SU_f(3)$ symmetry. The HAL collaboration has shown no repulsive core but attractive potential at a short distance in the baryon-baryon interaction in the $SU_f(3)$ singlet state, namely H-dibaryon channel. They suggest the H-dibaryon may appear as a weakly bound state or a resonant state near the $\Lambda\Lambda$ threshold. NPLQCD collaboration found the bound H-dibaryon in LQCD calculation without $SU_f(3)$ symmetry and also suggest the H-dibaryon around the threshold. We propose to search for the H-dibaryon resonance in $\Lambda\Lambda$ production from (K^-, K^+) reactions off nuclei and the bound H-dibaryon by its weak decays to answer the long-standing question about the existence of the H-dibaryon. For this experiment, we propose to construct a large acceptance hyperon spectrometer with a Time Projection Chamber (TPC) to detect Λ particles with high statistics and an excellent energy resolution. This spectrometer will also enhance the capability of hadron physics at J-PARC.

1 Introduction

The H-dibaryon was predicted to be a stable 6 quark state due to QCD color magnetic force by R.Jaffe more than thirty years ago [1]. The H-dibaryon is a singlet state among many 6 quark states under $SU_f(3)$ symmetry and consists of $ssuudd$ quarks in $I = J = 0$ state. Since then, many works have been made both theoretically and experimentally, which were summarized in ref.[2]. All the experiments searched for the stable H-dibaryon ended up with negative results. Whereas, observation of the weak decay of double hypernuclei gave a lower limit of the mass of the H-dibaryon [3]. The most stringent lower limit so far was determined by the mass of ${}^{6}_{\Lambda\Lambda}$He observed by the KEK-E373 hybrid-emulsion experiment [4]. The lower limit of the H-dibaryon mass is about 7 MeV below the $\Lambda\Lambda$ threshold. Following these experimental results the existence of a bound H-dibaryon is considered to be very unlikely.

J.K.Ahn et al., (KEK-E224) observed an enhancement near the $\Lambda\Lambda$ threshold in the invariant mass spectrum as shown in Fig.1 [5]. In this experiment, two Λ particles were produced in the (K^-, K^+) reactions off carbon nuclei and observed in a scintillating-fiber active target. This peak structure was confirmed by the following experiment KEK-E522 by a similar method with an improved statistics as shown in Fig.2 [6]. However, the $\Lambda\Lambda$ spectrum is consistent with theoretical calculations with expected $\Lambda\Lambda$ final state interactions within statistics. This peak can be interpreted as an H-dibaryon resonance of the mass of 2242 MeV/c^2, just 12 MeV/c^2 above the threshold. Due to the poor statistics, however, it was not possible to give definite conclusion whether there exists the H-resonance or not near the $\Lambda\Lambda$ threshold.

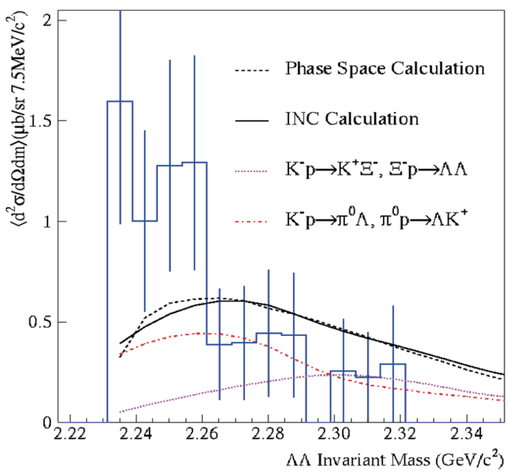


Figure 1: The $\Lambda\Lambda$ invariant mass spectrum (E224) compared to the 3-body phase space and an intra-nuclear cascade calculation. The cross sections for two two-step processes are also shown. Enhancement near the threshold compared to the calculations was seen [5].

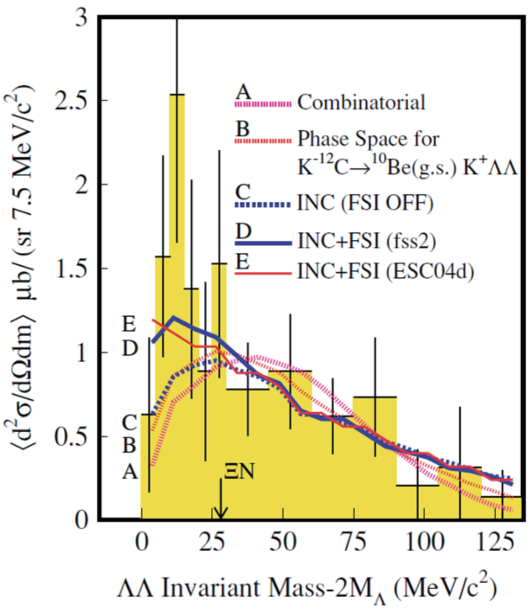


Figure 2: The $\Lambda\Lambda$ invariant mass spectrum (E522) compared to calculations, phase space (A), intra-nuclear cascade (INC) calculations without final state interaction (B) and with final state interactions (C,D). Although a peak structure is found at 2242 MeV/c^2, the data is consistent with calculations with final state interactions within the statistics [6].

Recently, a success of Lattice QCD calculation on the nucleon-nucleon interaction has attracted much attention [7]. The nuclear force, attractive potential at long distance and short range repulsion, was reproduced by the first principle calculation for the first time (Fig.3). The HAL collaboration extended this Lattice QCD calculation to the baryon-baryon interactions including hyperons under $SU_f(3)$ symmetry [8]. Very recently, they published the result of calculations on the two-body potential of the singlet state, namely the H-dibaryon state [9]. Fig. 4 shows the obtained potential which shows no repulsive core but deep attractive potential at a short distance. The result is stable against the lattice sizes from 2 to 4 fm. The calculations were made with three pion masses from 1015 to 673 MeV. Although the masses are still far from the real mass, the results seem to have a weak mass dependence. This striking result is qualitatively consistent with various quark model calculations based on the color-magnetic interaction and generalized Pauli principle among quarks. From this potential the H-dibaryon appears as a bound state with its binding energy, B_H, of $35.6 \pm 7.4 \pm 4.0$ MeV and rms distance of 1 fm at the pion mass of 673 MeV. This result was obtained under $SU_f(3)$ symmetry.

The H-dibayon state can be written with known hyperons as follows,

$$H = -\sqrt{1/8}\Lambda\Lambda + \sqrt{3/8}\Sigma\Sigma + \sqrt{4/8}\Xi N \qquad (1)$$

In the real world of $SU_f(3)$ breaking, the quoted binding energy B_H is interpreted as the

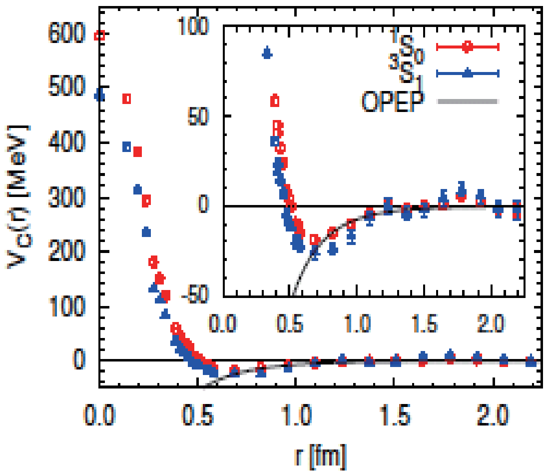


Figure 3: The nucleon-nucleon potential obtained with a Lattice QCD calculation by Ishii, Aoki and Hatsuda [7]. They qualitatively reproduce the nuclear force from the first principle.

binding energy from the average mass of two octet baryons. In the paper [9] it is claimed that; " considering that the difference between this average and 2 Λ mass is about the same amount to B_H, the H-dibaryon may appear as a weakly bound state or a resonant state near $\Lambda\Lambda$ threshold. " [9].

NPLQCD collaboration has made the LQCD calculation using Luscher 's method without $SU_f(3)$ $(n_f = 2+1)$. They have found that the H-dibaryon is bound with the binding energy of $B_H = 16.6 \pm 2.1 \pm 4.5$ MeV at even smaller pion mass of 389 MeV [10]. They discussed the extrapolation of the B_H to the physical point with use of both HAL and NPLQCD results and concluded that the H-dibaryon should be located around the $\Lambda\Lambda$ threshold [11] (see Fig.5).

Considering these Lattice QCD calculation results and the previous experimental results (KEK-E224 and E522) which showed a hint of H-dibaryon resonance, we believe it is quite important to experimentally answer the question about the existence of the H-dibaryon and conclude this long standing problem.

We propose to measure the same reaction, $\Lambda\Lambda$ production off nuclei, with a K^- beam at J-PARC. To obtain much higher statistics and better mass resolution, we propose to construct a large acceptance hyperon spectrometer with a Time Projection Chamber (TPC) to utilize a high intensity beam at J-PARC. We expect to obtain 3300 $\Lambda\Lambda$ events within 100 shifts and mass resolution of 1.0 MeV, compared to the previous KEK-E522 experiment where about 90 events were observed with a mass resolution of 5 MeV. We also search for $\Sigma^- p$ and $\Lambda\pi^- p$ decays inflight of the bound H-dibaryon in the TPC if it exists.

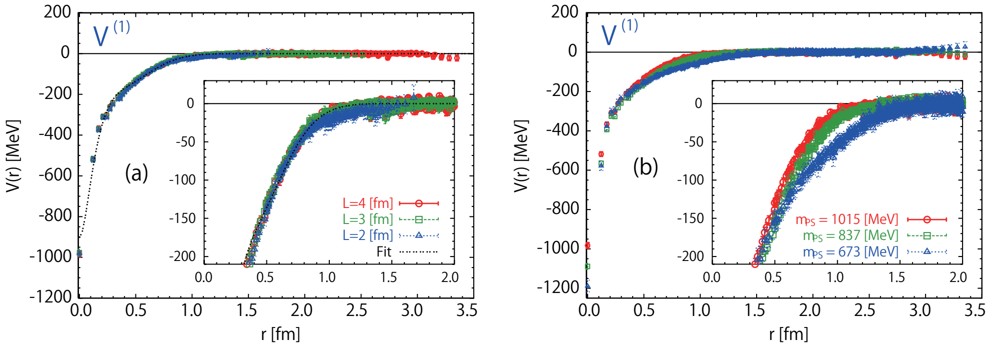


Figure 4: The BB potential in the $SU_f(3)$ singlet state calculated with Lattice QCD by HAL collaboration [8]. There is no repulsive core in this H-channel. (a) shows the lattice size dependence from 2 to 4 fm and (b) shows pion mass dependence from 673 to 1015 MeV.

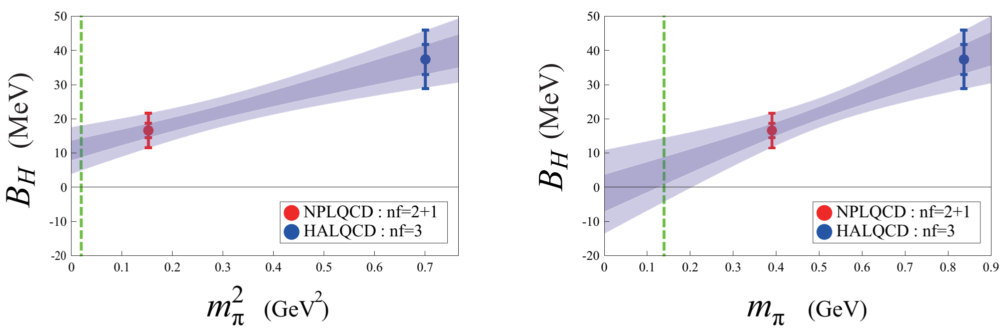


Figure 5: The results of LQCD calculation on H-dibaryon from HAL (blue) and NPLQCD (red) collaborations. The extrapolation of the LQCD results with a quadratic function of the pion mass (left panel) and a linear function (right panel) to the physical point(green dashed line).

2 Experiment

2.1 The goal of the proposed experiment

The first goal of the experiment is to conclude whether the previously observed enhancement near the $\Lambda\Lambda$ threshold is the H-resonance or not. The observed enhancement provided the central value of the mass (2250MeV) and the production cross section of about $1\mu b/sr$ for the possible H-resonance. With the proposed experimental apparatus which is described in the next section, we have simulated an expected spectrum of the $\Lambda\Lambda$ invariant mass. The simulated result is shown in Fig.6, where the H resonance yield is assumed to be the central value of the observed enhancement and expected mass resolution described in the following section. The momentum resolution ($\Delta p/p$) of decay particles from Λ is assumed to be 3% at $p = 300$ MeV/c and intrinsic H width is assumed to be zero in the simulation. The second goal is to provide more stringent upper limit for the production of H-dibaryon.

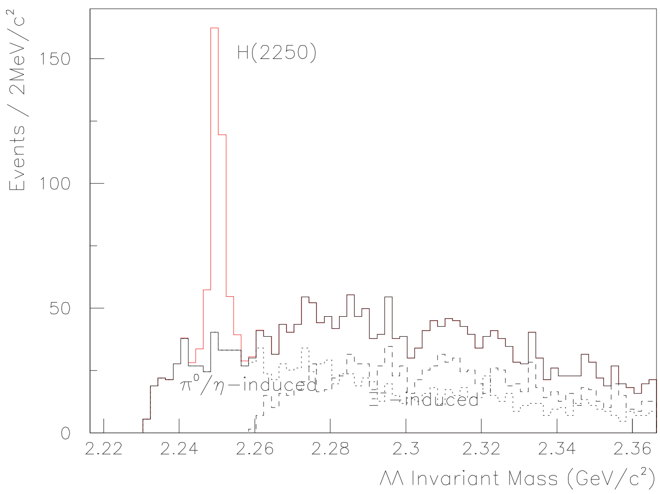


Figure 6: The result of the simulation for $\Lambda\Lambda$ invariant spectrum expected in the proposed experiment, if the previously observed peak is really due to the H-resonance. The width is determined by detector resolutions (the intrinsic H-width is assumed to be zero).

A.Aerts and C.Dover made theoretical calculations for the production of the H-dibaryon through (K^-, K^+) reaction off nuclei through $K^-pp \rightarrow K^+H$ reaction [12]. Many experiments have been done based on this expectation and excluded the H-dibaryon up to mass of about $2200MeV/c^2$ [13] as shown in Fig.7. However these experiments were not sensitive to this expected cross section if the H-dibaryon mass is near the $\Lambda\Lambda$ threshold because of the large tail of quasi-free Ξ^- production and other processes. The second goal is to conclude about the existence of the H-dibaryon assuming the production cross section

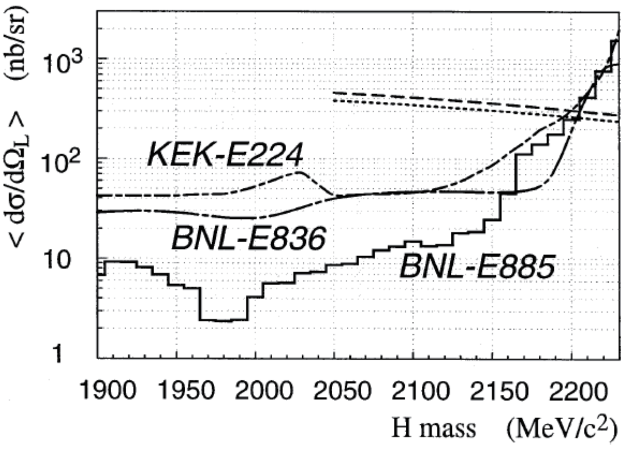


Figure 7: The 90% C.L. upper limits on the direct H-dibaryon production cross sections on ^{12}C (BNL-E885), shown together with the upper limits obtained in E224 and E836 (^{3}He target). The dashed and dotted lines show the theoretical calculations by Aerts and Dover for ^{12}C and ^{3}He, respectively. The upper limits are similar to the calculations at around 2210 MeV.

of about $0.2\mu b/sr$ given for ^{3}He target by A.Aerts and C.Dover. The simulated result is shown in Fig.8 for heavier targets the expected cross section becomes larger than 0.2μb/sr.

There still remains a possibility of the bound H-dibaryon if the mass is between the $\Lambda\Lambda$ threshold and 7 MeV below. In this case, it decays weakly to Λn, $\Sigma^{-}p$, Σ^{0}n and $\Lambda\pi^{-}p$ in flight. Among them, $\Sigma^{-}p$ and $\Lambda\pi^{-}p$ decays can be detected with the proposed experimental setup. These decay modes were actually searched for with a scintillating fiber active target in E224 and null result provided an upper limit of the production cross section as $0.6 \sim 0.7$ % of quasifree Ξ^{-} production cross section [14]. In the case of the scintillating fiber detector, secondary interactions which show similar pattern as $\Sigma^{-}p$ decay, limited a sensitivity. The proposed experiment will have 100 times higher sensitivity than E224 due to higher K^{-} beam intensity and gas detector. The result of the simulation where the H-dibaryons of 2220 MeV (just below the threshold) are produced in the (K^{-}, K^{+}) reactions and decay to $\Lambda\pi^{-}p$ in flight is shown in Fig.9. The background is due to misidentification of $\Lambda\Lambda$ events as $\Lambda\pi^{-}p$ events.

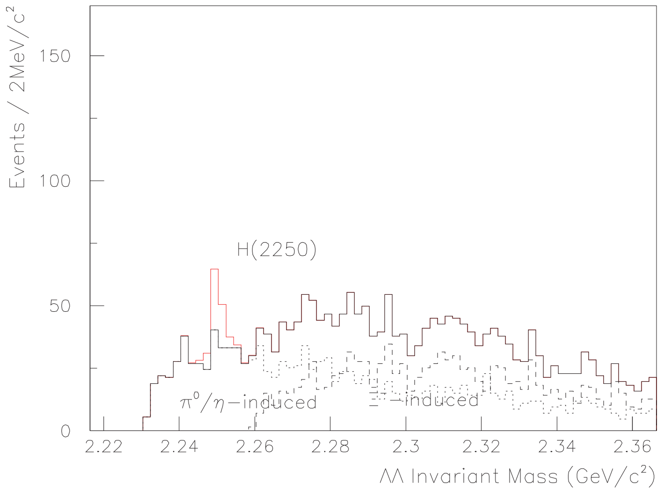


Figure 8: The result of the simulation for $\Lambda\Lambda$ invariant spectrum expected in the proposed experiment, if the H-dibaryon resonance is produced with the cross ection of 0.2 μb/sr predicted by A.Aerts and C.Dover [12] .

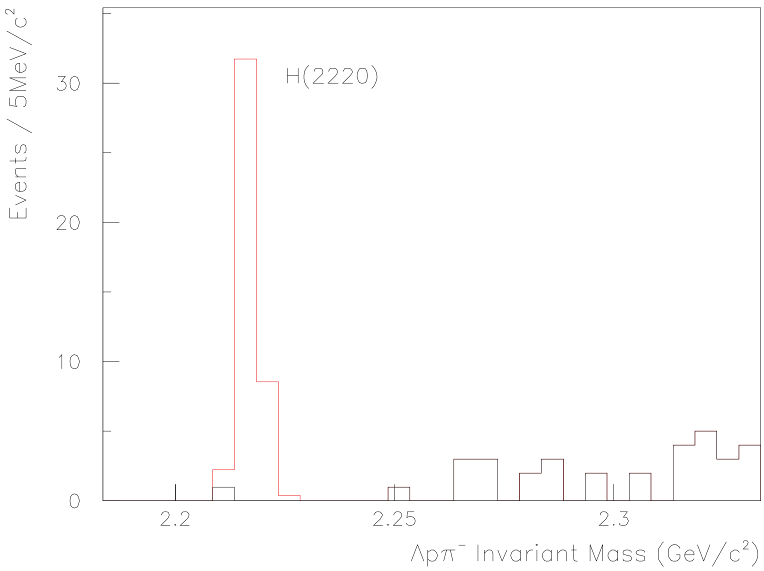


Figure 9: The results of the simulation for the invariant mass spectrum for $\Lambda\pi^{-}$p decayed from the bound H-dibaryon of 2220 MeV. The production cross section is ssumed to be 0.2μb/sr as predicted by A.Aerts and C.Dover.

2.2 Experimental setup

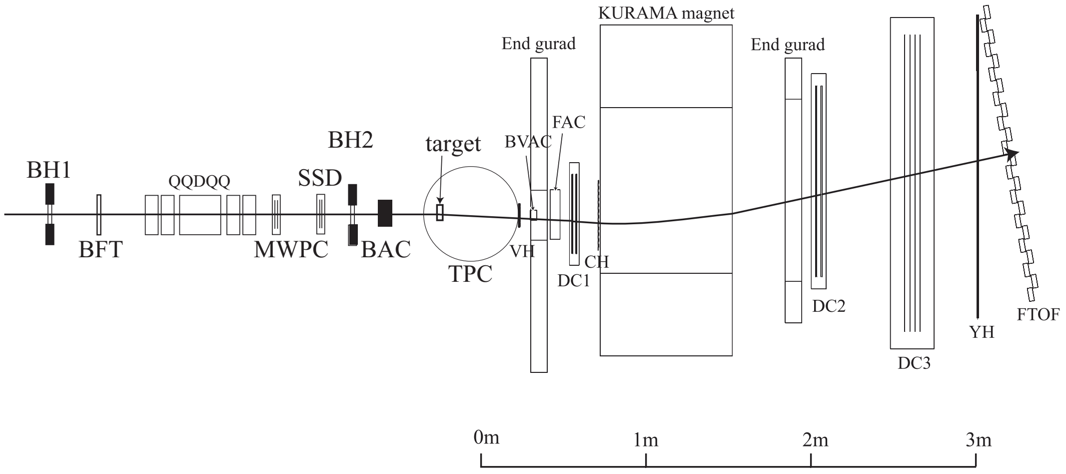
We will measure (K^-, K^+) reaction off nuclei with use of the 1.8 GeV/c K^- beam at J-PARC and the Kurama K^+ spectrometer. In addition, we will construct a large acceptance hyperon spectrometer with TPC to detect Λ particles to search for the H-resonance. The experimental setup is shown in Fig.10. The K^- beam particles are identified with aerogel Cherenkov detectors and TOF measurement. The out-going K^+ particles are identified by the Kurama spectrometer with aerogel Cherenkov and TOF detectors. The second level trigger will be introduced to veto protons as was done at similar experiments at KEK and BNL.

The $\Lambda\Lambda$ is produced through the two step reactions; $K^-(p) \to \pi^0\Lambda, \pi^0(p) \to K^+\Lambda$ and $K^-(p) \to K^+\Xi^-, \Xi^-(p) \to \Lambda\Lambda$. These two step processes are known to be approximately proportional to $A^{2/3}$ [15]. We employ a Cu target to obtain the larger cross section and larger acceptance for Λ particles, since if they decay inside the target, a mass resolution will be significantly deteriorated. The target is located inside the TPC, at the upstream part of TPC to efficiently detect hyperons of short flight lengths.

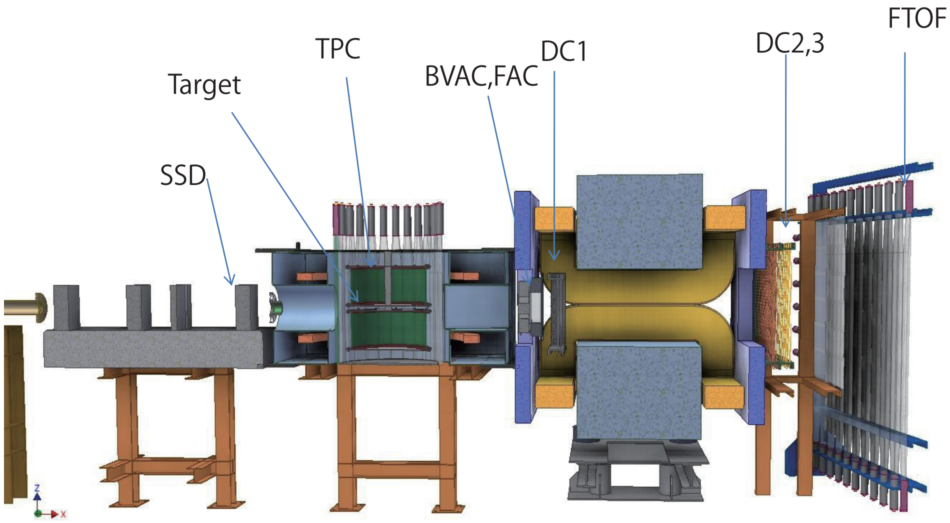
2.3 Yield estimation

The yield estimation for $\Lambda\Lambda$ events has been made under following conditions.We expect to detect 3300 $\Lambda\Lambda$ events in 100 shifts of beam time, which is about 100 times more than those observed in the previous KEK-E224 experiment. If the H-dibaryon cross section is 0.2μb/sr as predicted, the number of the observed H-dibaryon is expected to be about 46 events.

Parameters	Values
K^- beam	$10^6 K^-$ per spill (6 second)
Cu target	4.25×10^{22}
$d\sigma/d\Omega_L^{Cu}(\Lambda\Lambda)$	14.6μb/sr
$\Delta\Omega$	0.11 sr
Branching ratio ($\Lambda \to p\pi^-$)	0.64
Detection efficiency of K^+ with Kurama	0.5
Detection efficiency of two Λ with TPC	0.5
Yield	0.007 event / spill



(a)



(b)

Figure 10: A schematic view (a) and layout (b) of the experimental setup. The Kurama spectrometer is almost same as the one used in KEK-E522 and written in the correct sizes but the K1.8 beam line spectrometer and the hypTPC spectrometer are only schematically shown.

2.4 A large acceptance hyperon spectrometer with TPC (HypTPC)

Two Λ particles produced from the Cu target are detected with a large acceptance hyperon spectrometer with TPC (HypTPC) which consists of a magnet and a TPC. It is shown schematically in Fig.11. The magnet field of about 1 T is provided by a superconducting Helmholz type magnet. About 20 cm gap of two coils allow incoming K^- particles and out-going K^+ particles to be detected with the Kurama spectrometer. The effective field volume is about 50 cm in diameter and 50 cm in length. The TPC has a cylindrical shape to fit into the magnet. The signals are amplified and read with GEM sheets and anode pads at both ends of the TPC. With a position resolution of $300\mu m$ the pion momentum resolution of about 1% is expected at 300 MeV/c which is the average pion momentum from Λ particles. The TPC is operated under a beam intensity of about $10^6 K^-$ per spill. Therefore, a gating grid is employed for the triggered operation of the TPC. A prototype TPC with GEM readout was constructed at JAEA and test measurements are now underway (see Fig.11). The detailed design of the HypTPC will be made following the results of the test measurements.

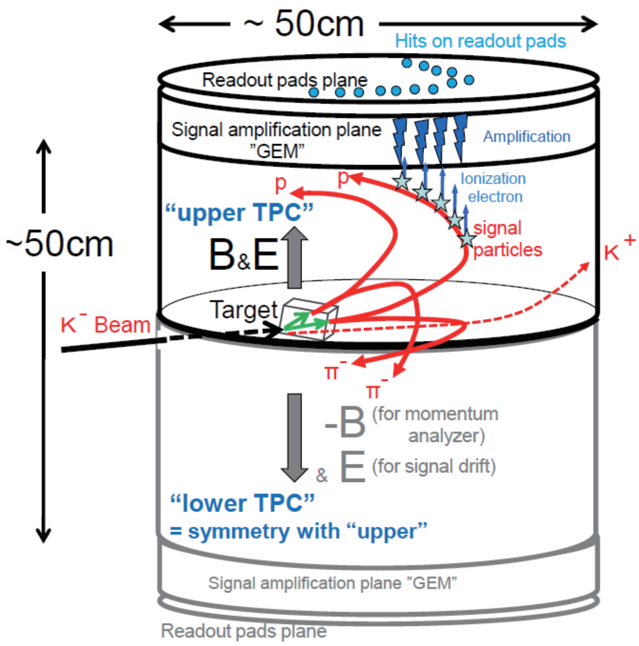


Figure 11: A schematic view of TPC for HypTPC spectrometer. The Helmholts type magnet is not shown in the figure. The target is located inside the TPC. Drifted electrons are amplified through 3 layers of GEM plates and read out with anode pads.

3 Summary

Recent Lattice QCD calculation, which succeeded to reproduce the nucleon-nucleon potential, has been extended to baryon-baryon interactions in $SU_f(3)$ symmetry by HAL collaboration. They have shown no repulsive core but attractive potential at a short distance in the baryon-baryon interaction in the $SU_f(3)$ singlet state, namely H-dibaryon channel. They suggest the H-dibaryon may appear as a weakly bound state or a resonant state near the $\Lambda\Lambda$ threshold. NPLQCD collaboration found the bound H-dibaryon in LQCD calculation without $SU_f(3)$ symmetry and also suggest the H-dibaryon around the threshold. We propose to search for the H-dibaryon resonance in $\Lambda\Lambda$ production from (K^-, K^+) reactions off nuclei and the bound H-dibaryon by its weak decays to answer the long-standing question about the existence of the H-dibaryon. For this experiment, we propose to construct a large acceptance hyperon spectrometer with a Time Projection Chamber (TPC) to detect Λ and other particles with high statistics and an excellent energy resolution. We expect to observe 3300 $\Lambda\Lambda$ events in 100 shifts of beam time with the mass resolution of 1.0 MeV. This spectrometer will also enhance the capability of hadron physics at J-PARC.

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