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High-resolution hypernuclear decay pion spectroscopy at MAMI and future

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Summary. — Hypernuclear decay pion spectroscopy was established in 2012 at MAMI as a mass spectroscopy method for light hypernuclei. A monochromatic pion peak from ${}^{4}_{\Lambda}\mathrm{H}$ was successfully observed, and the Λ binding energy was determined to be $B_{\Lambda} = 2.157 \pm 0.005(\mathrm{stat.}) \pm 0.077(\mathrm{syst.})$ MeV in the 2014 run. In 2022, an upgrade experiment for ${}^{3}_{\Lambda}\mathrm{H}$ spectroscopy was conducted using a newly developed Li target. The absolute electron beam energy will be measured by the synchrotron radiation interferometry, which will be applied with the spectrometer calibration to improve the systematic error. The decay pion spectroscopy is planned to be performed at JLab Hall-C, which would significantly increase the statistics thanks to the higher energy beam, the better K^{+} identification, and the faster data acquisition system. This experiment has been submitted as a Letter of Intent in JLab PAC51. The upgraded decay pion spectroscopy method is expected to provide new, accurate hypernuclear data, which will contribute to the advancement of our understanding of hypernuclear physics.

(*) On behalf of the A1 Hypernuclear Collaboration.

1. – Measurements of hypernuclear binding energies

The accurate measurement of Λ binding energies of Λ hypernuclei (B_Λ) is very essential for the discussion of the effective interaction between a Λ and a nucleon in a nuclear medium. Most of B_Λ's on *s*- and *p*-shell hypernuclei were measured with emulsions in the 1960s and 1970s [1]. Recently, new data on $^{3}_{\Lambda}\mathrm{H}$ have been reported, as invariant mass spectroscopy of hypernuclei has become possible with heavy ion beams [2-4]. In particular, the STAR Collaboration reported deeper B_Λ and shorter lifetimes than previous results with emulsions, which have been discussed as the "hypertriton puzzle". Precise spectroscopy of iso-mirror hypernuclei is useful to discuss charge symmetry breaking of the ΛN interaction and neutron-rich hypernuclei to discuss ΛN-ΣN coupling effects. In this context, the $(e, e'K^+)$ reaction spectroscopy has been conducted at JLab. This technique, which uses the primary electron beam, allows for high-resolution spectroscopy at sub-MeV level. The decay pion spectroscopy method was developed as a novel approach to achieve better resolution spectroscopy of light mass hypernuclei at the Mainz Microtron (MAMI) of Johannes Gutenberg University Mainz, Germany.

Section **2** describes the principle of the decay pion spectroscopy and recent results at MAMI. Section **3** presents the planned application of the decay pion spectroscopy that is planned at JLab.

2. – Decay pion spectroscopy of Λ hypernuclei

The decay pion spectroscopy was designed to measure the absolute mass of the ground state of light hypernuclei with high precision. A proof-of-principle experiment was conducted in 2012 at MAMI, which provides a high-energy (1.508 GeV maximum) continuous electron beam. The first observation of the $^{4}_{\Lambda}\mathrm{H}$ peak was successfully achieved, and data collection was conducted in 2014 and 2022 with updates to the experimental setup.

2˙1. *Principle.*

– Figure 1 shows the principle of the decay pion spectroscopy. In this technique, the mass of a parent hypernucleus is deduced by measuring the momentum of the weak decay pion emitted by the two-body decay. If the parent hypernucleus stops in the production target, the Λ binding energy (B_Λ) can be described as follows:

$$B_\Lambda = \left(\sqrt{M_N^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}\right) - \left(M_{core} + M_\Lambda\right), \tag{1}$$

where M_{core}, M_Λ, M_N, and M_π are the mass of the core-nucleus, the Λ, the daughter nucleus, and the π^-, respectively, and those are well known. p_π is a momentum

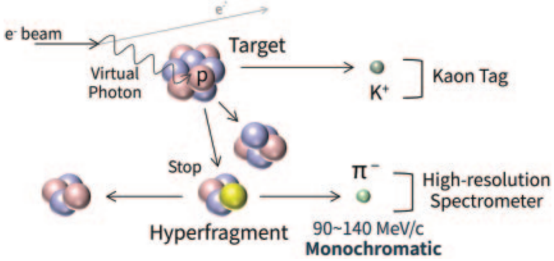

Fig. 1. – Principle of the hypernuclear decay pion spectroscopy.

of decay charged pion from hypernuclear weak decay that we measure precisely. The characteristics of the technique are as follows:

i) This technique allows the measurement of both direct-produced hypernuclei and hyperfragments where the Λ is bound to a fragmented nucleus.

ii) Hypernuclear nuclides can be identified from the peak momentum, as the pions have a unique momentum for each parent hypernuclear nuclide.

iii) K^+ is used to tag events in which strange particles are produced to suppress background.

iv) Since the masses of the daughter nucleus and the π^- are known very well, B_Λ can be deduced by measuring the low momentum π^- around 100 MeV/c.

v) The technique is complementary to the missing mass and the gamma-ray spectroscopy because of its high resolution but lacks of sensitivity to the excited states of hypernuclei.

A thin target of several tens to a hundred mg/cm^2 is necessary to reduce the energy straggling effect of decay π^-s. A high-intensity beam is necessary to produce enough hypernuclei even on a thin target. In existing facilities, this method can be applied only at MAMI and JLab, which can provide high-intensity electron beams.

In the MAMI experiments, we have employed the existing high-resolution spectrometers (Spek-A and Spek-C) as pion spectrometers, the large solid angle spectrometer (Kaos) as a K^+ tagger, and a 38 mg/cm^2 ^{9}Be target.

2˙2. *Results.* – The decay pion spectroscopy was performed in 2012 and 2014 at MAMI. In the 2012 data taking, the first decay pion momentum peak from $^4_\Lambda$H was successfully observed. The peak resolution in terms of binding energy was 200 keV in FWHM, which is several times better than the resolution of the $(e, e'K^+)$ experiments. The peak was fit by un-binned negative log-likelihood using the peak shape estimated by the Monte-Carlo simulation. The peak position was evaluated to be $B_\Lambda(^4_\Lambda\mathrm{H}(0^+)) = 2.12 \pm 0.01(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})\,\mathrm{MeV}$ [5]. The pion spectrometers Spek-A and Spek-C were calibrated using the elastic scattering events of a beam electron and a target nucleus (^{12}C and ^{181}Ta). The systematic errors were dominated by the uncertainty of the absolute value of the electron beam energy in the calibration process, together with the instability of the spectrometer itself during data taking.

In the 2014 data taking, a vacuum extension was utilized to connect the target chamber and the spectrometer vacuum chamber, thereby improving resolution. Additionally, the spectrometer instability was improved to suppress systematic errors. Consequently, $B_\Lambda(^4_\Lambda\mathrm{H}(0^+)) = 2.157 \pm 0.005(\mathrm{stat.}) \pm 0.077(\mathrm{syst.})\,\mathrm{MeV}$ was obtained [6]. Combined with the gamma-ray spectroscopy of the $^4_\Lambda$He excited state, the level structure of the $A = 4$ hypernuclei was updated and the ΛN charge symmetry breaking was found to be spin-dependent.

2˙3. *Upgrade experiments at MAMI.* – Although B_Λ of $^4_\Lambda$H has been successfully measured, no other hypernuclear peaks have been found. Therefore, we decided to use a Li target, which is expected to have a higher yield of $^3_\Lambda$H than the Be target. The Li target requires countermeasures to apply the decay pion spectroscopy due to difficulties such as oxidation in the atmosphere, poor thermal conductivity, a low melting point, and an increased thickness due to its low density. To address these difficulties while maintaining sufficient luminosity, a target of 50 mm in the beam axial direction and 750 μm in width was introduced [7]. The beam intensity was reduced to μA, which was $\sim$1/10 of the previous experiments, to prevent it from melting. The new Li target was mounted on a water-cooled copper frame with an efficient cooling mechanism. Thus, the new target was able to ensured the hypernuclear yield by maintaining an excellent π^- resolution.

Most of the systematic errors in the previous decay pion spectroscopy are dominated by the beam energy uncertainty during the spectrometer calibration. Synchrotron radiation interferometry from two undulators will be introduced as a novel technique to measure the absolute electron beam energy around 100 MeV to suppress the systematic error [8, 9]. The Lorentz factor γ of the electron beam passing through the undulators can be described as $\gamma^2 = \lambda_{osc}/2\lambda_{rad}$, where λ_{osc} is the oscillation period as a function of the distance between the two undulators and λ_{rad} is the wavelength of the synchrotron radiation. From feasibility tests, the γ has been successfully measured with an accuracy of 10^{-4}. Suppose the absolute beam energy can be measured with this accuracy. In that case, an accuracy improvement of about one order if magnitude can be achieved by a better spectrometer calibration, and we expect the total B_Λ error to be $\sim$ten keV.

The data taking with the new Li target was performed in 2022 and is being analyzed. A spectrometer calibration will be conducted using synchrotron radiation interferometry.

3. – Future decay pion spectroscopy project at JLab

The decay pion spectroscopy has been successful at MAMI. However it is crucial to improve yields to measure different hypernuclear species. A significant yield improvement would be difficult since the MAMI setup has constraints such as beam energy, K^+ identification performance, DAQ rate, and dose level. We are considering carrying out the decay pion spectroscopy at the JLab, in which the $(e, e'K^+)$ missing mass spectroscopy with Ca, Pb, and some light-mass targets is approved [10,11]. Further mass spectroscopy using lighter mass number targets such as Li, Be, and B is also submitted as a Letter of Intent [12, 13].

We propose to install a third spectrometer (Enge) as a pion spectrometer in addition to the two high-resolution spectrometers to be used in the $(e, e'K^+)$ experiment, as shown in fig. 2 [14]. This setup allows to perform the decay pion experiment in with the $(e, e'K^+)$ experiment. Enge is a high-resolution spectrometer used in the previous hypernuclear experiments at JLab. Enge has good momentum resolution (4×10^{-4}) and wide momentum bite (70–170 MeV/c), which is well suited for decay pion spectroscopy.

The advantages of the experiment at JLab are the following:

i) The JLab hypernuclear program will use much higher beam energy (2.24 GeV) than MAMI experiments. Efficient hypernuclear production is possible. The yield gain is expected to be about five, thanks to the higher beam energy.

ii) The JLab experiments use the High-Resolution Kaon Spectrometer (HKS) which can be employed as a K^+ tagger in the decay pion spectroscopy. Better particle identification performance of HKS helps us to suppress background and the DAQ trigger rate. In addition, the JLab DAQ system is about ten times faster than the MAMI system. We expect to get about ten times higher yield per unit time.

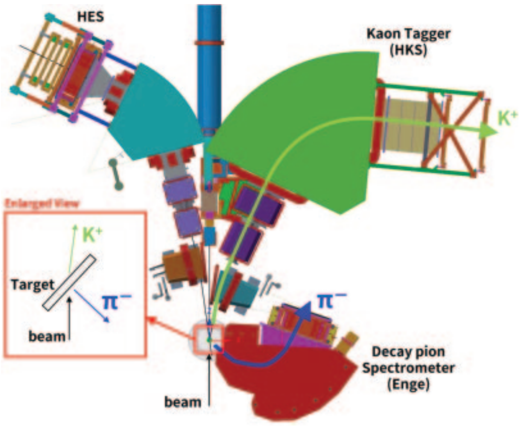

Fig. 2. – Proposed setup of decay pion spectroscopy at JLab [14].

iii) The $(e, e'K^+)$ experiments will run by changing targets for about a half year. If decay pion spectroscopy can be carried out in parallel, collecting data for long periods without requiring significant additional beamtime is possible.

Consequently, if the experiment is conducted at the Jefferson Laboratory, ~30 times more statistics will be collected than in the MAMI experiment. Furthermore, the Λ binding energies of several hypernuclei will be newly determined with an accuracy of approximately 10 keV. These precise results are expected to provide essential inputs to discuss ΛN interaction property.

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