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Preparation of the hypertriton binding energy measurement at MAMI

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A new experiment is being prepared at the Mainz Microtron (MAMI) to determine the Λ binding energy of hypertriton. The energy will be measured by the spectroscopy of mono-energetic pions from two-body decays of stopped hyperfragments. During the last decade, it has been demonstrated at MAMI that this technique yields an unprecedented precision. The new experiment makes use of a novel high-luminosity target that takes advantage of the low density of lithium to minimize momentum smearing for the outgoing pions. With a beam energy determination by the novel undulator light interference method an improved calibration of the magnetic spectrometers can be performed to reach the goal of a statistical and systematic error of $\sim 20\,\text{keV}$.

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1. Λ binding energies of hydrogen hypernuclei

The hypertriton, ${}^{3}_{\Lambda}$H, is a benchmark nucleus for hypernuclear structure calculations and plays a fundamental role in strangeness nuclear physics, comparable to the deuteron in non-strange nuclear physics. Its Λ binding energy is of high importance for understanding the Λ–N interaction and can be used to constrain state-of-the-art calculations which describe the ${}^{3}_{\Lambda}$H internal structure.

Since almost 50 years, the most precise binding energy value is given by $B_\Lambda = 130 \pm 50\,$keV, averaged and compiled from emulsion experiments [1]. Recently, two new values became available, one by the STAR Collaboration [2], $B_\Lambda = 406 \pm 120\,(\text{stat.}) \pm 110\,(\text{syst.})\,$keV, and a preliminary one by the ALICE Collaboration [3], $B_\Lambda = 50 \pm 60\,(\text{stat.}) \pm 100\,(\text{syst.})\,$keV. Both were determined from relativistic heavy ion experiments with very large sets of collected collisions.

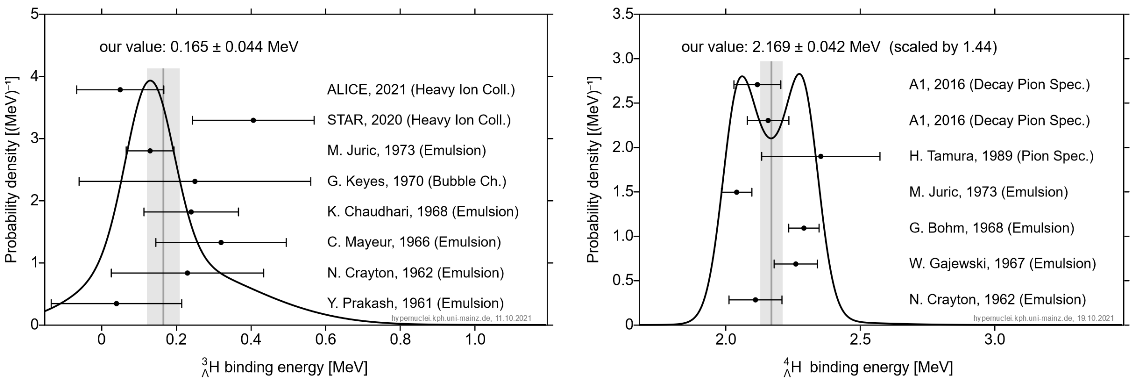

Figure 1: Ideograms of the world data sets on Λ binding energy measurements for ${}^{3}_{\Lambda}$H (left) and ${}^{4}_{\Lambda}$H (right) [4]. The error bars include statistical and systematic uncertainties. In case of ${}^{4}_{\Lambda}$H , the data have been conservatively handled by computing a scaling factor $S = \sqrt{\chi^2/ndf}$ and multiplying it with the error. Our averages are $B_\Lambda({}^{3}_{\Lambda}\text{H}) = 0.165 \pm 0.044\,$MeV and $B_\Lambda({}^{4}_{\Lambda}\text{H}) = 2.169 \pm 0.042\,$MeV.

Remarkably, the STAR value is about 8 times larger than the preliminary one from ALICE and they differ by two standard deviations. The STAR value also seems to be in tension with the emulsion value. These data along with earlier measurements are visualized in an ideogram in the left panel in Fig. 1. An average value of $\overline{B_\Lambda} = 165 \pm 44\,$keV is computed with a relative error of still more than 25 % [4]. In addition, any underestimated error or bias in one of the three cited values is directly affecting the world average. For the emulsion technique, the calibration procedure and the selection criteria based on χ^2 values are discussed in Ref. [1]. A systematic error of $\pm 40\,$keV, given in Davis' reviews [5], is the so-far best estimate for the accuracy of the procedure and has been included in our averages.

In the right panel of Fig. 1 the ideogram for ${}^{4}_{\Lambda}$H is shown, including two values from previous decay-pion experiments by the A1 Collaboration [6] and several emulsion values [1]. Correlated errors in the A1 data were treated explicitly adopting the PDG procedure [7]. The resulting probability density distribution has a structure with two maxima and a χ^2/ndf greater than 1, but not greatly, suggesting that the errors of one or more contributing measurements are underestimated. Not knowing which of the errors are underestimated, they are all multiplied by the same factor $\sqrt{\chi^2/ndf}$. The relative error of the average is $\sim 20\,\%$.

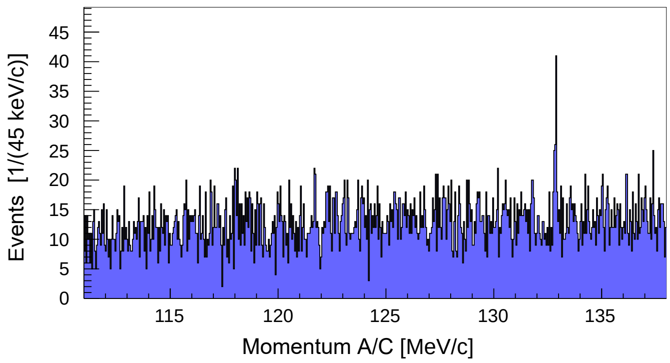

Figure 2: Momentum spectrum for strangeness tagged pions from the 2014 measurement at MAMI [11]. Mono-energetic decay-pions of ${}^{4}_{\Lambda}$H were observed at $\sim$ 133 MeV/c. A signal from two-body decays of stopped ${}^{3}_{\Lambda}$H was not found at the expected momentum of $\sim$ 114 MeV/c.

To further complicate the situation, there have been attempts to recalibrate earlier B_Λ values using the current best estimates of the masses of particles and nuclei [2, 8]. Such a recalibration would be very significant for light hypernuclei, especially for the hypertriton, where it amounts to approximately 100 keV. However, systematic errors possibly occurring in the emulsion analysis due to an outdated Λ mass are partially compensating in the applied procedure [5]. This means that a recalibration cannot be performed in the suggested way.

As the data situation for these light hypernuclei is clearly not satisfactory, a new high-precision experiment via decay-pion spectroscopy is in preparation at MAMI with the goal to reach a 20 keV systematic error in the binding energy [9, 10]. Within the upcoming experiment, both, ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H, are expected to be observed.

2. Decay-pion spectroscopy at MAMI

2.1 Experimental technique

By using a high-energy electron beam, a ΛK^+ pair can be created via strangeness electroproduction in a target nucleus. If this Λ stays bound within the nucleus, a highly excited hypernucleus is formed that de-excites, e.g. by the emission of one or more nucleons, so that eventually a lighter hypernucleus is left in its ground state. Note that the Λ lifetime, τ_Λ = 263 ps, and the related hypernuclei lifetimes are long enough, so that the hypernucleus survives the fragmentation process and in many cases the stopping within the target material. Then, a weak decay occurs at rest. In case of a two-body decay, the pion and the recoiling nucleus are emitted back-to-back and are mono-energetic. Hence, the mass of the hypernucleus $m_{\text{hyp.}} = \sqrt{m^2_{\text{nucl.}} + p^2_\pi} + \sqrt{m^2_\pi + p^2_\pi}$ can be determined by measuring the momentum of charged decay-pions p_π in a magnetic spectrometer and the precisely known pion and nucleus masses. The probability of such a strangeness electroproduction reaction is rather small compared to other background reactions, so the emitted kaon has to be detected in coincidence with the decay pion. That way only "strangeness tagged" events are recorded. The method was successfully applied at MAMI within the last decade [6]. Data were taken with beryllium targets of thicknesses between 23 and 47 mg/cm^2. Fig. 2 shows a representative momentum spectrum, where decay pions of ${}^{4}_{\Lambda}\mathrm{H}$ are clearly visible at around 133 MeV/c, resulting in a binding energy of $B_{\Lambda} = 2.157 \pm 0.005\,(\mathrm{stat.}) \pm 0.077\,(\mathrm{syst.})$ MeV. The systematic error was strongly dominating because the spectrometer calibration was limited by the available MAMI beam energy measurement with an accuracy of 160 keV. The beam spread and instability are known to be much smaller. Consequently, any improvement in the beam energy measurement can reduce the error of the experiment. An accuracy of 15 keV for the beam energy is possible with the novel undulator light interference method [12].

The experiment as well as the spectrometer calibrations are planned for the year 2022.

2.2 Novel high-luminosity lithium target

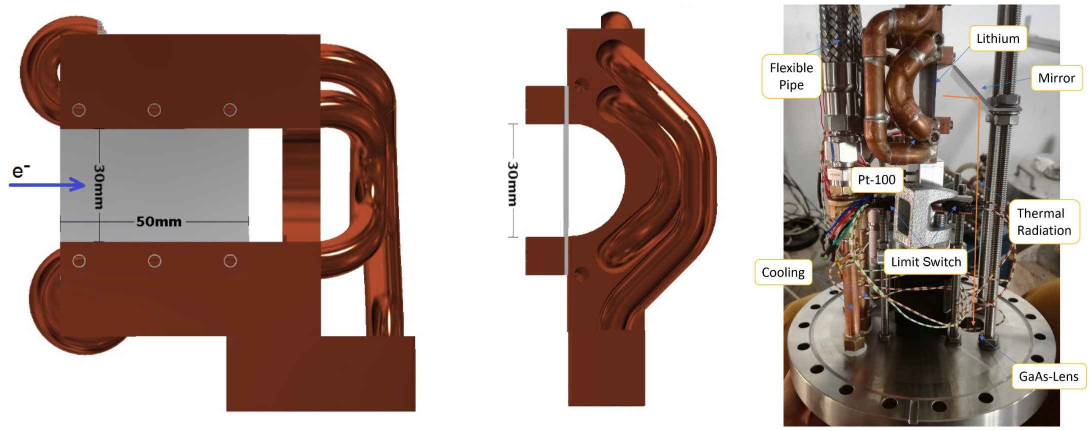

Figure 3: Prototype of the high-luminosity lithium target at MAMI [13]. Left: Design drawings. Right: Photograph. The lithium sheet has a thickness of 2.7 g/cm^2 in beam direction. In the upper part of the setup, flexible pipes for the cooling liquid can be seen, next to the copper body for the optimal removal of heat from the lithium sheet. A polished metal plate deflects the infrared light towards a lens in the flange to monitor the temperature. In the lower part, a stepper motor, a planetary gearbox, and a limit switch are located.

Lithium provides a higher ${}^{3}_{\Lambda}\mathrm{H}$ yield than beryllium as it has fewer possible fragmentation channels. Furthermore, its low density allows a target geometry such as the one shown in Fig. 3 with dimensions $1.5 \times 50 \times 50\,\mathrm{mm}^3$. The electron beam will traverse 50 mm of material, resulting in a thickness of 2.7 g/cm^2, about 100 times thicker than the previously used beryllium target. The small transverse dimension limits the energy-loss variations of the decay pions.

Lithium has a low melting point of 180° C, so the target frame is made of copper in which a cooling fluid circulates. To control the state of the target during the experiment, a visual monitoring system was developed based on a thermal camera and infrared optics [10]. As shown in Fig. 4, its field of view covers the complete side of the target. Beam tests have demonstrated that a temperature of 70° C was not exceeded at a beam intensity of 10 μA. As a material, lithium is difficult to handle due to its high reactivity, it can form oxides and nitrates in air. The alignment of the target inside of the scattering chamber is performed in vacuum with a rotary and a linear stage. The camera system can be used to monitor the relative alignment of target and beam as seen in Fig. 4.

It is planned to install a second camera on the opposite side of the target which allows for a stereoscopic view of the temperature distribution inside the lithium sheet. Thus, the alignment procedure might benefit from the comparison of the two thermal images.

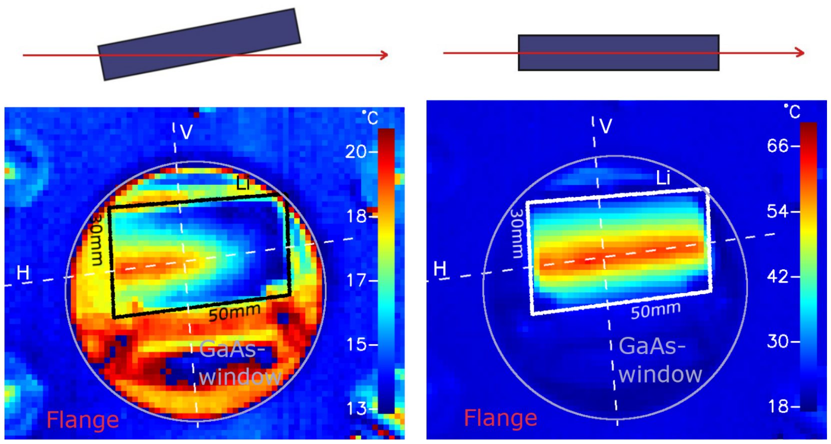

Figure 4: Thermal images of the lithium target during tests with a 855-MeV electron beam at MAMI [13]. Vertical (V) and horizontal (H) directions and the outlines of the target and the window are indicated. The alignment of target and beam is schematically depicted at the top. Left: Target and beam misaligned at a beam intensity of 2 μA. The lithium was only partially heated and its temperature stayed near room temperature. Right: Proper alignment at a beam intensity of 10 μA. The temperature remained below 70° C.

Acknowledgments

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References

[1] M. Jurić et al., *Nucl. Phys. B* **52** (1973) 1; G. Bohm et al., *Nucl. Phys. B* **4** (1968) 511.

[2] STAR Collaboration, *Nat. Phys.* **16** (2020) 409.

[3] P. Fecchio, ALICE Collaboration, 2021, indi.to/3MvSH.

[4] P. Eckert, P. Achenbach et al., 2021, hypernuclei.kph.uni-mainz.de.

[5] D.H. Davis, *Nucl. Phys. A* **547** (1992) 369; D.H. Davis, *Nucl. Phys. A* **754** (2005) 3c.

[6] A1 Collab., *Phys. Rev. Lett.* **114** (2015) 232501; A1 Collab., *Nucl. Phys. A* **954** (2016) 149.

[7] Particle Data Group, *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01.

[8] P. Liu et al., *Chinese Phys. C* **43** (2019) 124001.

[9] P. Achenbach, S. Bleser, J. Pochodzalla and M. Steinen, *PoS (Hadron2017)* **207** (2018) 1.

[10] P. Achenbach et al., in *Proc. Hadron2019*, pp. 713, 2020, 10.1142/9789811219313_0123.

[11] F. Schulz, PhD thesis, Johannes University Mainz, 2016, 10.25358/openscience-4548.

[12] P. Klag et al., *Nucl. Instrum. Methods Phys. Res. A* **910** (2018) 147.

[13] P. Herrmann, PhD thesis, Gutenberg University Mainz, 2021, 10.25358/openscience-6299.