The hypernuclear physics program at Jefferson Lab

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Summary. — Missing mass spectroscopy of Λ hypernuclei using the $(e, e'K^+)$ reaction has been performed in the past at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) by several experiments in Halls A and C. A new experimental campaign is expected to start running in 2026 in Hall C and to provide the first study of the isospin dependence in medium-mass hyperisotopes by populating $^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K using isotopically enriched calcium targets [E12-15-008]. During this campaign, it will be possible to study Λ interactions in nuclear matter using a lead target [E12-20-013]. Solid-state targets made of lithium, beryllium, and boron [LOI12-23-013], and aluminum [LOI12-23-016] are considered to be included in the campaign. The use of the HKS and HES spectrometers together with thin target foils and high beam currents leads to a sub-MeV energy resolution, significantly better than in hadron beam experiments. Valuable information on few-body hyperon systems would be gained if helium targets were used [E12-19-002]. Using an additional spectrometer for measuring the decay-pion spectra could give access to the binding energies of light hyperfragments [LOI12-23-011]. The measurement of precise and accurate energy spectra of different hyperisotopes probes the Λ-N interaction in nuclei including the Λ-N-N interaction. The latter is assumed to play a key role for the stiffness of the nuclear equation-of-state relevant for the stability of neutron stars.

1. – Strange nuclear physics at Jefferson Lab

Hypernuclear experiments have been performed at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) and other electron beam accelerators and spectrometer

(*) On behalf of JLab Hypernuclear Collaboration facilities. Intense beams with energies above 1 GeV and complexes of focusing magnetic spectrometers operated in coincidence provide high spectroscopic resolutions and unique information for our understanding of nuclear forces. The hypernuclei that are formed in these electroproduction reactions are isotopic mirrors of those formed in meson-induced two-body reactions.

Experimentally, high-precision $(e, e'K^+)$ spectroscopy is a powerful tool for strangeness nuclear physics. To exploit its full potential, it requires

i a high survival probability and the correct identification of the charged kaons for tagging the associated strangeness production, typically achieved with short-orbit spectrometers and Cherenkov detectors;

ii a good choice of kinematic conditions compatible with the instrumental limitations and providing statistical significant yields for the population of ground and excited hypernuclear states, including the detection of the outgoing electrons at small scattering angles to maximize the virtual photon flux and the detection of the kaons at angles close to the virtual photon direction where the momentum transfer to the nucleus is minimum, typically achieved with additional magnetic beam-line elements;

iii high relative momentum resolutions of $\delta p/p < 1 \times 10^{-3}$ and accurate absolute momentum calibrations of the spectrometers for identifying and separating the hypernuclear states, typically achieved with lower energy beams and by utilizing the elementary strangeness electroproduction reactions $p(e, e'K^+)\Lambda, \Sigma^0$.

Several hypernuclear campaigns at Jefferson Lab have been performed in Halls A and C on p-shell and medium-mass targets. Reaction spectroscopy data were taken for ${}^{7}_{\Lambda}$He [1, 2], ${}^{9}_{\Lambda}$Li [3, 4], ${}^{10}_{\Lambda}$Be [5], ${}^{12}_{\Lambda}$B [6, 7], and ${}^{16}_{\Lambda}$N [8] utilizing different magnetic spectrometers, targets, beam-lines, particle identification methods, and kinematics.

Due to the tight schedule of Hall A, in which the installation of the MOLLER experiment will begin in early 2025, the hypernuclear experiments will be performed in Hall C instead of the originally planned Hall A. The expected signal-to-background ratio in the hypernuclear binding-energy spectra and the hypernuclear yields are lower than the original expectations for the setup in Hall-A. The collaboration has adjusted the coming campaign accordingly, which includes a change in the kinematics and a substantial increase of the requested beam time. It is planned to re-install the High-resolution Kaon Spectrometer (HKS) for K^+ detection with a central momentum of $p_K = 1.200\,\mathrm{GeV}/c$ and the High-resolution Electron Spectrometer (HES) in horizontal configuration for e' detection with a central momentum of $p_{e'} = 0.740\,\mathrm{GeV}/c$, both combined with a Pair of Charge-Separation magnets (PCS) for an optimized forward acceptance. The magnetic fields of the PCS have a minimal effect on the primary electron beam while the previously used single large dipole deflected the electron beam and optically coupled the kaon spectrometer and the electron spectrometer, both effects are unwanted and resulted in very complicated beam tune and analysis. As the HES spectrometer was designed for electrons of less than $1\,\mathrm{GeV}/c$ momentum, the incident electron beam energy is limited to 2.5 GeV to keep the virtual-γ energy at 1.5 GeV. It is proposed to use an electron beam energy of $E_e = 2.240\,\mathrm{GeV}$ with beam currents of $50\,\mu\mathrm{A}$ on production targets. The layout of the experimental set-up common to the approved experiments is shown in Fig. 1. Both spectrometers have been used in the previous hypernuclear experiments in Hall C at Jefferson Lab and are equipped with fully commissioned drift chambers,

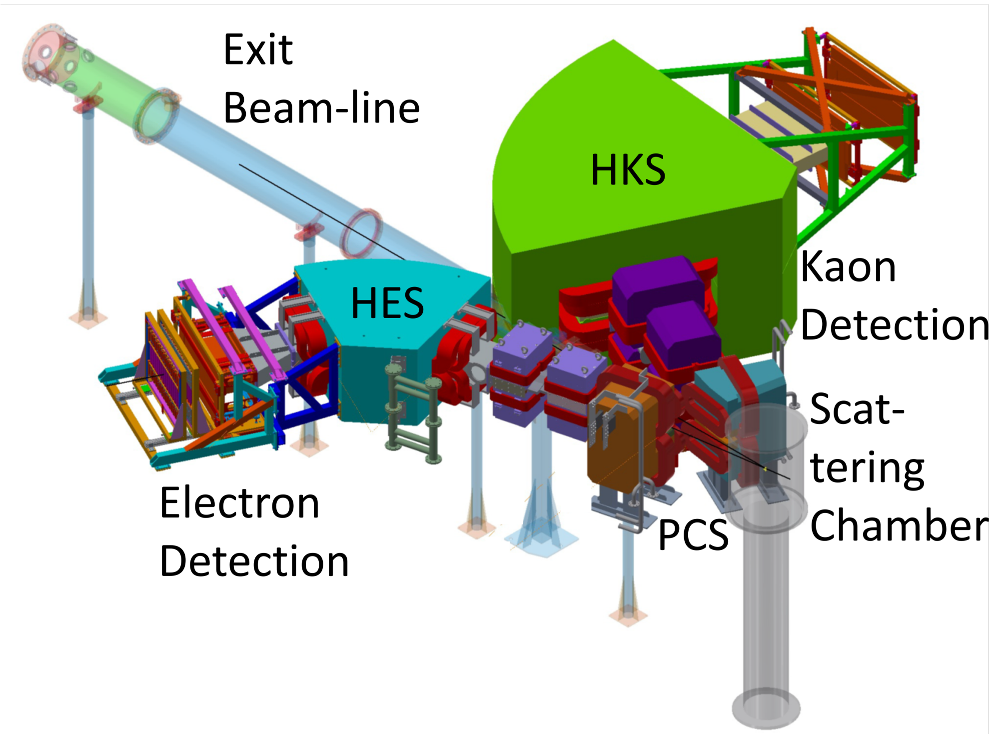

Fig. 1. – Layout of the set-up in Hall C of Jefferson Lab for the hypernuclear experiments. The electron beam enters from the bottom right. A Pair of Charge-Separation magnets (PCS) is seen behind the scattering chamber that encloses the target system, followed by the electron spectrometer HES left of the beam-line and the kaos spectrometer HKS right of it. Both spectrometers are equipped with detector packages for triggering, tracking, and particle identification.

time-Of-flight walls, and Cherenkov detectors. Analysis software packages for HKS and HES exist. The solid angle acceptances of the spectrometers are 8.2 msr for HKS and 4.4 msr for HES. The newly designed PCS has been constructed in 2020 and delivered to Jefferson Lab in 2022. The horizontal configuration of both spectrometers, HES and HKS, provides no vertex resolution along the beamline and thus only allows for thin targets such as solid-state foils, but not for gas targets. However, it has slight advantages for the momentum and mass resolutions. Based on initial Geant4 [9] simulations, relative momentum resolutions of below 5×10^{-4} (FWHM) and a missing-mass resolution of $0.5\,\mathrm{MeV}/c^2$ were projected. A set-up time of several months in the experimental hall is required before the experiments are ready to take beam.

Section **2** is describing the main physics topic addressed by the upcoming campaign. In Section **3**, the current status of the proposals presented to the Jefferson Lab Program Advisory Committees are reviewed, followed by Section **4** for the letters of intent. Section **5** concludes with a short summary.

2. – Hypernuclear physics and neutron stars

A common theme in almost all of the proposed hypernuclear experiments at Jefferson Lab is their connection to neutron star physics through the nuclear equation-of-state (EOS). The two-nucleon and three-nucleon interactions do allow for the observed neutron stars of two solar masses, but the densities in a neutron star are such that hyperons will be present. Inclusion of the Λ-N interaction stiffens the EOS, but not by enough to enable a two solar mass star. State-of-the art calculations of neutron matter with modern two- and three-body hyperon-nucleon interactions indicate that the three-body interaction becomes repulsive at high density and could enable the EOS to sustain a two solar mass star [10].

Charge symmetry holds in QCD because of the near mass-degeneracy of the fundamental up (u) and down (d) quarks. In nuclei, the symmetry holds to better than 1 %. In Λ hypernuclei, charge symmetry breaking (CSB) is manifest in the charge or isospin dependence of Λ binding energies. In the light mass region, several isospin doublets exist such as (${}^{4}_{\Lambda}$H,${}^{4}_{\Lambda}$He) and (${}^{8}_{\Lambda}$Li,${}^{8}_{\Lambda}$Be), and ${}^{7}_{\Lambda}$He and ${}^{7}_{\Lambda}$Be belong to an isospin triplet with the excited $I = 1$ state in ${}^{7}_{\Lambda}$Li*. Experimentally, a sizable CSB effect in the $A = 4$ isospin mirror pair has been observed by comparing the excitation energy of the $J^{P} = 1^{+}$ state in ${}^{4}_{\Lambda}$H with the results of a precision measurement of the γ-transition in ${}^{4}_{\Lambda}$He in an experiment at J-PARC [11]. The experimental data [12, 11] strongly support the fact that the $A = 4$ hypernuclear iso-doublet has a large CSB in its 0^{+} ground states and a small CSB in its excited 1^{+} states. Uncertainties in the experimental data for the $A = 7, 8, 9$, and 10 isospin multiplets complicate the determination of the size of the CSB effect in heavier systems [13, 14]. Although the origin of a large CSB is not fully understood, the inclusion of Λ-N–Σ-N couplings and 3-body forces to the $\Lambda - N$ interaction has become essential. This not only has consequences for the description of strange nuclear systems, but is also influential in constructing the neutron star EOS.

The Λ binding energy represents one of the most fundamental quantities in understanding the Λ-N interaction and Λ hypernuclear structure [15]. The proposed experiments to study hypernuclear binding energies will aid the resolution of the puzzle associated with the role of hyperons in determining the maximum mass of neutron stars.

3. – Proposals

3˙1. *E12-15-008: An isospin dependence study of the* Λ*-N interaction through the high precision spectroscopy of* Λ *hypernuclei with electron beam.* – This experiment seeks to explore the isospin dependence of the three-body Λ-N-N interaction in ${}^{40}_{\Lambda}$K and ${}^{48}_{\Lambda}$K by measuring the binding energy of both hypernuclei. This investigation should give insight into a specific coefficient, C_T of the Λ-N-N interaction, and the measurement should be able to reach a 2 % accuracy in this quantity if the binding energies can be measured with a 100 keV accuracy. The coefficient would be clearly constrained by the experiment according to recent AFDMC calculations. With C_T known from experiment, the three-body interaction can be used in calculations of the mass-radius relation for neutron stars.

The proposal was approved with rating A by PAC44 in 2016 and re-approved by PAC51 in 2023 [16, 17].

3˙2. *E12-19-002: High accuracy measurement of nuclear masses of* Λ *hyperhydrogens.* – The experiment aims to make a precision measurement of the binding energy of ${}^{3}_{\Lambda}$H and

${}^{4}_{\Lambda}$H. Experiments providing high-precision information about few-body hyperon systems are needed especially to refine hyperon-nucleon interactions and the CSB terms.

The experiment was proposed for running in Hall A. However, it could not get scheduled in this hall due to the start of the installation the Moeller experiment, but is expected to run in Hall C. The different setup in this hall, in particular the unavailability of spectrometers with a vertical bend and z-vertex measurement capability, is imposing some difficulties for realizing it in its original design.

The proposal was approved with rating A by PAC49 in 2021 [18].

3˙3. *E12-20-013: Studying* Λ *interactions in nuclear matter with the* ${}^{208}Pb(e, e'K^+){}^{208}Tl$ *reaction.* – This experiment focuses on measuring the excitation spectrum of ${}^{208}_{\Lambda}$Tl obtained from the ^{208}Pb$(e, e'K^+){}^{208}_{\Lambda}$Tl reaction with an energy resolution of 0.8 MeV. The data may be exploited to achieve a largely model-independent analysis of the measured cross section, based on the established formalism of nuclear many-body theory.

The measurement is proposed to use the same experimental apparatus as for experiment E12-15-008 with the exception of a new cryogenic-cooled Pb target. Using a heavier target with larger neutron access as compared to the ^{40}Ca and ^{48}Ca targets of experiment E12-15-008 provides an as good as possible proxy of matter in the interior of a neutron star.

The proposal was approved with rating $B+$ by PAC48 in 2020 [19].

4. – Letters of Intent

4˙1. *LOI12-23-011: High-resolution spectroscopy of light hypernuclei with the decay-pion spectroscopy.* – The experiment, proposed in 2023 [20], aims at measuring Λ binding energies for s- and p-shell hypernuclei using high-resolution decay-pion spectroscopy. This method has been pioneered at the Mainz Microtron MAMI in the last decade and provides an unprecedented precision [12]. The design accuracy on the Λ binding energies is about 10 keV, while it was several tens of keV or more in previous experiments [21]. The expected results would not only lead to a better understanding of Λ-N interactions, but would also shed light on Λ-N–Σ-N coupling and the hyperon puzzle in neutron stars.

For this experiment, pions need to be detected in coincidence with the outgoing particles from the studied $(e, e'K^+)$ reactions, using the Enge magnet as a decay-pion spectrometer, while HKS and HES detect the kaon and the scattered electron. The experiment is proposed to run simultaneously to the other hypernuclear physics experiments. Additional beam-time for the carbon target is requested for a larger yield of decay-pions from the produced hyperfragments.

4˙2. *LOI12-23-013: Study of charge symmetry breaking in p-shell hypernuclei.* – The experiment, proposed in 2023 [22], will study the ^{6}Li$(e, e'K^+){}^{6}_{\Lambda}$He, ^{9}Be$(e, e'K^+){}^{9}_{\Lambda}$Li, and ^{11}B$(e, e'K^+){}^{11}_{\Lambda}$Be reactions. The design resolution on the binding energy is 70 keV, which is precise enough for a meaningful comparison of the binding energies with those of the isospin partners, which will be measured at J-PARC in the (π^+, K^+) reaction channel. The origin of CSB is an open question, and the proposed studies of the p-shell hypernuclei are indispensable to gain knowledge on the origin of CSB.

The experiment will use the same experimental setup as the approved experiments. Isotopically enriched materials of ^{6}Li, ^{9}Be, and ^{11}B with thicknesses of 100 mg/cm^2 are proposed as targets.

4·3. *LOI12-23-016: Study of a triaxially deformed nucleus using a Λ particle as a probe.* – The experiment, proposed in 2023 [23], aims to establish a completely new application of hypernuclear studies that have never been explored before. Triaxially deformed nuclei such as ^{26}Mg are known from studies of γ-ray transitions. A Λ particle in p-orbit of a hypernucleus has a wave function that is extending in a certain direction, which produces shifts in energy levels depending on which axis of the triaxially deformed core nucleus the wave function is oriented. By measuring this difference in $^{27}_{\Lambda}$Mg with the ^{27}Al$(e, e'K^+)^{27}_{\Lambda}$Mg reaction, it is possible to investigate triaxially deformed nuclei from the inside using the Λ particle as a probe.

The setup will be shared with the approved experiments, and a ^{27}Al target foil of $100\,\mathrm{mg/cm^2}$ thickness will be used.

5. – Summary

The high-energy electron beam produced at Jefferson Lab is an ideal probe to study the hadronic structure of nuclei and nucleons and permitted the first successful $(e, e'K^+)$ spectroscopy on nuclei. This reaction, in contrast to most meson-induced reactions, produces hypernuclei by converting a proton into a hyperon and transfers a large momentum to a hypernucleus. The smaller cross section for the reaction compared to the strangeness exchange reaction n$(K^-, \pi^-)\Lambda$ or to the associated production n$(\pi^+, K^+)\Lambda$ is well compensated by the available high electron beam intensities. The experiments are scheduled to take place in Hall C of Jefferson Lab in an extended campaign using a common setup with different solid-state targets.

Studies of hyperon-nucleon interactions provide a unique approach to explore the baryon-baryon interaction. In such studies, the information on hypernuclear structure obtained by spectroscopic measurements plays an essential role in testing and improving interaction models and to understand high-density nuclear matter inside neutron stars.

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