Hypernuclear physics as seen by an experimenter

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In the new millennium hypernuclear physics is undergoing a renewed interest, both theoretically and experimentally.

Hadrons and nuclei are understood as many-body systems made of quarks and gluons, bound by the strong force. Information on baryon-baryon interactions is mainly obtained from nuclear experiments with projectiles and targets out of nucleons, addressing interactions in flavour SU(2) only. The difficulties to study hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions by reaction experiments are related to the practical problems in the preparation of low energy hyperon beams and the impossibility of hyperon targets due to the short ($\sim$200 ps) life-times of hyperons. The investigation of a hypernucleus, where one or more nucleons have been replaced by one or more hyperons, allows addressing a rich spectrum of physics topics ranging from genuine nuclear physics to particle physics. Although fifty years have already passed since the discovery of the first hypernuclear events, studies of hypernuclei are still at the forefront of nuclear physics. The presence of the hyperon can induce several effects on the host nucleus, like changes of both size and shape, modification of cluster structure, manifestation on new symmetries or changes of nucleon collective motions. One of the most spectacular effects, observed so far in what is called impurity nuclear physics, is the shrinking of the nucleus core. Such a behaviour can be considered a precursor of matter condensation induced by strange particles.

Only recently, it has already been demonstrated that hypernuclei can be used as a micro-laboratory to study YN and YY interactions. In the case of ΛN interaction, the spin-orbit term has been found to be smaller than that for the nucleon. In a recent experiment at BNL the spacing of the $(5/2^+, 3/2^+)$ doublet in $^9_\Lambda$Be was measured to be (43 ± 5) keV [1]. Although these small spin splittings can only be observed using gamma spectroscopy, reaction spectra are equally important because they provide the complete spectrum of excitations. In addition, experimental data on medium to heavy single Λ hypernuclei have shown a much larger spin-orbit splitting than observed in light hypernuclei [2].

Hypernuclei physics, born and developed mainly in Europe, has seen a renaissance at the turn of the century. Until now, experimental information has mainly come from meson-induced reactions and most recently from coincident γ-ray spectroscopy of hypernuclei. Even though a number of new experimental techniques have been developed for the hypernuclear spectroscopy in the last decade, our knowledge is still limited to a small number of hypernuclei. The large

variety of novel experimental approaches to hypernuclei will provide a wide basis for a comprehensive understanding of strange hadrons in cold nuclear systems. The spectroscopy of single Λ- and double ΛΛ-hypernuclei will remain one of the most valuable tools for the experimental investigation of strangeness nuclear physics in the near future.

1   The hypernuclear programme at MAMI

At the Institut für Kernphysik in Mainz, Germany, the microtron MAMI has been upgraded to 1.5 GeV electron beam energy and can now be used to study strange hadronic systems [3].

Electron beams have excellent spatial and energy definitions, and targets can be physically small and thin ($10 - 50 \, mg/cm^2$) allowing studies of almost any isotope. The cross-section for the reaction, $\sigma \sim 140 \, nb/sr$ on a ^{12}C target as first measured at Jefferson Laboratory in Experiment E89-009 [4], is small compared to strangeness exchange $n(K^-, \pi^-)\Lambda$ or associated production $n(\pi^+, K^+)\Lambda$. This smallness can be well compensated in electro-production by the available large electron beam intensities, but often the resulting electromagnetic background is limiting the reaction rates.
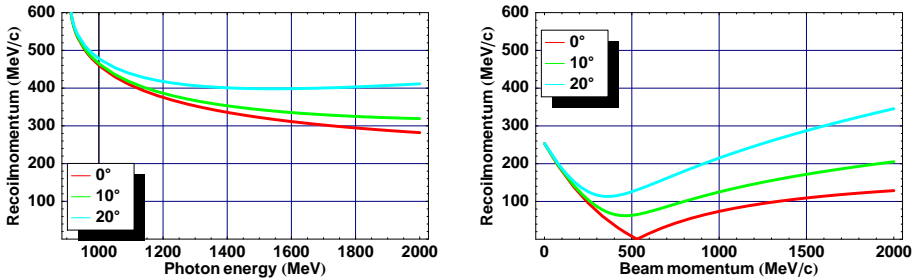

Fig. 1. Recoil momentum for strangeness electro-production (left) and strangeness exchange (right) reactions at three different kaon angles are shown as a function of the energy of the virtual photon, respectively the beam momentum. Reaction cross-sections and transition amplitudes to individual states depend strongly on the recoil momentum.

In order to produce a hypernucleus, the hyperon emerging from the reaction has to be bound in the nucleus. Reaction cross-sections and transition amplitudes to individual states depend strongly on the transferred momentum to the hyperon. If the momentum transfer is large compared with typical nuclear Fermi momenta, the hyperon will preferentially leave the nucleus. The (K^-, π^-) reaction is characterised by the existence of a "magic momentum" where the recoil momentum of the hyperon becomes zero as is shown Fig. 1. It populates, consequently, substitutional states in which a nucleon is converted to a Λ in the same state. The $(e, e'K^+)$ reaction, on the other hand, produces neutron-richer Λ hypernuclei converting a proton to a Λ hyperon and transfers a large recoil

momentum to a hypernucleus. This reaction is preferable when high-spin hypernuclear states are studied. In addition, this reaction has the unique characteristic of providing large amplitudes for the population of spin-flip hypernuclear states with unnatural parities [5], such as $({}_\nu p_{3/2}^{-1},{}_\Lambda s_{1/2})2^-$, where the spin quantum number, $J^P = 2^-$, of the nucleon-hole Λ-particle state has maximum $J = {}_\nu l + {}_\Lambda l + 1 = 1 + 0 + 1 = 2$.

KAOS is a very compact magnetic spectrometer suitable especially for the detection of kaons, that was used before at GSI in a single-arm configuration [6]. During the last years it was installed at the Mainz microtron MAMI in the existing spectrometer facility operated by the A1 collaboration [7]. In the very near future the spectrometer will be set-up for the first time with tracking detectors arranged in two arms, to either side of the main dipole. The special kinematics for electro-production of hypernuclei requires the detection of both, the associated kaon and the scattered electron, at forward laboratory angles. The KAOS spectrometer will cover simultaneously electron scattering angles close to $0°$ and kaon scattering angles around $5°$ up to $15°$ in order to extract dynamical information from the K^+ angular distribution [8].
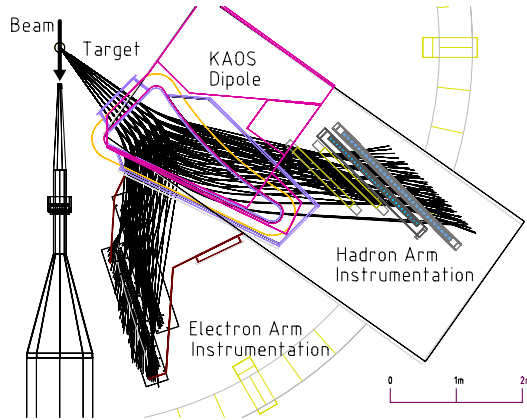

Fig. 2. Overview of the KAOS spectrometer of the A1 collaboration at the Mainz microtron MAMI: electrons and hadrons are detected simultaneously under small scattering angles. Charged particle trajectories through the spectrometer are shown by full lines. The electron arm tracking detector will be located close to the electron beam. High radiation levels are expected at that position.

The KAOS spectrometer's electron arm detectors will operate close to zero degrees scattering angle and in close proximity to the electron beam. Fig. 2 shows a schematic drawing of the set-up in the spectrometer hall. The magnet bends the central trajectory on both sides by ~45 degrees with a momentum dispersion of 2.2 cm/%. The first-order focusing is realized as seen in Fig. 2. In addition to a broad neutron spectrum high electromagnetic background levels are expected at the detector locations. It is consequently imperative to operate radiation hard and intrinsically fast detectors.

While the instrumentation of the hadron arm is operational, a new coordinate detector of the spectrometer's electron arm is under development [9,10]. It will consist of two vertical planes of fibre arrays (x and θ), covering an active area of $L \times H \sim 2000 \times 300\,\text{mm}^2$, supplemented by one or two horizontal planes (y and φ). The 18,432 fibres of the vertical tracking detectors will be connected to 4,608 electronics channels with logic signals fed into the level-1 trigger. The track information will be used to reconstruct the target coordinates and particle momentum, and the time information used to determine the time-of-flight of the particle from target to the detection planes. New front-end electronics has been developed for the fast signals of more than 4,000 MaPMT channels of the fibre detector in the KAOS spectrometer's electron arm.
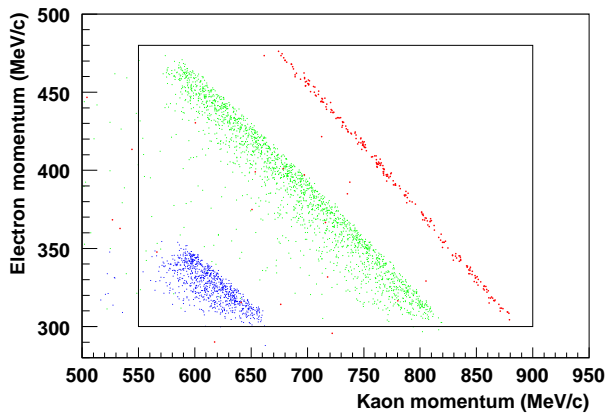

Fig. 3. (color online) Simulated correlation between electron and kaon momenta, where Σ (blue, left) and Λ (green, centre) hyperons have been generated for the elementary production off the proton and the $^{12}_{\Lambda}$B hypernuclei (red, right) have been generated for a carbon target. The rectangular box indicates the simultaneous momentum acceptance of the KAOS spectrometer in its two-arm configuration.

In Fig. 3 the simulated correlation in electro-production between the electron momentum and the kaon momentum is plotted, where Λ and Σ hyperons have been generated for the elementary production off the proton and the $^{12}_{\Lambda}$B hypernuclei have been generated for a carbon target. The events have been generated randomly in phase-space and weighted by a factor for the virtual photon flux and the modelled transition form factor. In the Monte Carlo, the production probability was assumed to drop exponentially with the relative momentum between Λ hyperon and core nucleus and typical values of $\sigma_p = 100\,\text{MeV}/c$ and $k_F = 200\,\text{MeV}/c$ were assumed. The rectangular box in Fig. 3 indicates the simultaneous momentum acceptance of the KAOS spectrometer. Its large momentum acceptance covers the quasi-free process as well as the hypernuclear production reaction. In practice, this fact will simplify the identification of the hypernuclear events in the data sample.

It is currently planned to perform a first experiment with two complete vertical planes of the fibre detector in the KAOS spectrometer's electron arm in 2009.

The hypernuclear programme will follow as soon as the two-arm configuration of the spectrometer is operational and the magnet optics is determined in such a way that sub-MeV mass resolution is possible. The latter situation is assumed to be reached in late 2009 or early 2010.

2   The HypHI experiment

Until recently hypernuclear spectroscopy has been restricted to the investigation of hypernuclei close to the valley of beta-decay stability as in most experiments targets made of stable nuclei are used with meson and electron beams. The recently proposed HypHI project (Hypernuclear spectroscopy with stable heavy ion beams and rare-isotope beams) is dedicated to hypernuclear spectroscopy with stable heavy ion beams and rare isotope beams at GSI, Germany, and FAIR, the Facility for Antiproton and Ion Research [11]. This approach has some advantages: firstly, it is possible to investigate a number of hypernuclei simultaneously in a single experiment and secondly the hypernuclei are created at extreme isospins. The observation of the Λ-hypernucleus decay modes offers the unique opportunity to look at the four-baryon, strangeness-changing, weak vertex. The determination of the relative weights of the different decay channels represents a long-standing puzzle. The HypHi project is divided into four phases. To study the feasibility of hypernuclear spectroscopy with heavy ion beams the phase 0 experiment was proposed [12], aiming at the identification of the π^- decay channels of $^3_\Lambda$H, $^4_\Lambda$H and $^5_\Lambda$He produced by ^{6}Li 2 AGeV beams impinging on a ^{12}C target of $8\,\mathrm{g/cm}^2$ mass.

Hypernuclear production via heavy ion collisions is described by the participant-spectator model and was first studied theoretically by Kerman and Weiss [13]. In the collisions hyperons are produced in the participant region with a wide rapidity distribution centered around mid-rapidity. Hypernuclei can be formed in coalescence of hyperon(s) in the projectile fragments, with the velocity of hypernuclei close to the projectile velocity with $\beta > 0.9$. Decays of hypernuclei can be studied in-flight, and most of their decay vertices are a few tens of a centimetre behind the target at which hypernuclei are produced.

The experimental set-up, which will consist of an analysing dipole magnet as well as time-of-flight (TOF) and tracking detectors, was designed to measure the invariant mass of particles decaying behind the target. The TOF branch will consist of a start detector and two position-sensitive TOF walls for positive and negative charged particles, placed behind the dipole. In addition, the scintillators will provide energy deposit information for the charge identification of the registered particles. Three tracking detectors made of scintillating fibres will be positioned between target and magnet and will be used to trigger readout system on events which contain a decay vertex behind the target. The fibre detector will also become crucial in distinguishing the hypernuclei $^4_\Lambda$H and $^3_\Lambda$H from the background containing α and Λ particles produced at the target.

A further advantage of this approach is that hypernuclei are produced as projectile fragments at beam rapidity that will open a way to direct measurements of hypernuclear magnetic moments. In meson and electron beam induced

experiments, recoil momenta of produced hypernuclei are small. Therefore, it has been impossible so far to conduct direct measurement on hypernuclear magnetic moments by means of spin precession in strong magnetic fields. This is one of the goals of the final project phase.

3   The hypernuclear programme at PANDA

The single hypernuclei research programme will be complemented by experiments on multi-strange systems with $\overline{\text{P}}$ANDA at the planned FAIR facility. The $\overline{\text{P}}$ANDA hypernuclear programme shall reveal the $\Lambda\Lambda$ strong interaction strength, not feasible with direct scattering experiments [14,15]. In the anti-proton storage ring HESR relatively low momentum Ξ^- will be produced in $\overline{\text{p}}\text{p} \rightarrow \Xi^-\overline{\Xi}^+$ or $\Xi^-\overline{\Xi}^0$ reactions. The associated $\overline{\Xi}$ will scatter or annihilate inside the residual nucleus. The annihilation products contain at least two anti-kaons that can be used as a tag for the reaction. Due to the large yield of hyperon-antihyperon pairs produced a high production rate of single and double hypernuclei in an active secondary target under unique experimental conditions will be feasible. High resolution γ-ray spectroscopy based on high-purity germanium (HPGe) detectors represents one of the most powerful means of investigation in nuclear physics: the introduction of this technique determined a significant progress in the knowledge of the nuclear structure. Consequently, for the high resolution spectroscopy of excited hypernuclear states an efficient, position sensitive HPGe array is foreseen. To maximise the detection efficiency the detectors must be located as close as possible to the target. Hereby the main limitation is the load of particles from background reactions. Most of the produced charged particles are emitted into the forward region. Since the γ-rays from the slowly moving hypernuclei are emitted rather isotropically the HPGe detectors will be arranged at backward axial angles $\theta \geq 100°$. A full simulation of the hypernuclei detector's geometry has been completed.
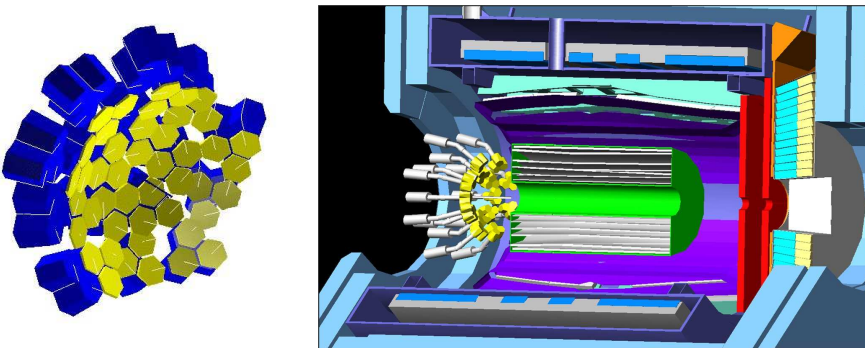

Fig. 4. Simulated set-up with HPGe cluster detectors (left) situated at backward angles for hypernuclei experiments at $\overline{\text{P}}$ANDA (right). The beam enters from left.

Fig. 4 shows the simulated γ-ray spectroscopy set-up with several HPGe cluster detectors (each comprising 3 crystals). A small fibre barrel read-out by silicon photomultiplier has been discussed as an option for a time-of-flight start detector to identify hypernuclear reactions. For this sub-detector system the achievable time resolution at minimum detector mass is a main issue.

The hypernuclear physics addressed by this experiment is currently discussed in the upcoming „$\overline{P}$ANDA Physics Book". In the planned set-up there exist many experimental challenges and several European research groups are working on the realisation of the detectors. A detailed design will be available in the mid-term future. When reflecting upon the state of the preparations for this set-up, one should be aware that the construction of the anti-proton storage ring and the $\overline{P}$ANDA experiment has not yet started.

Acknowledgements

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