Detector developments for the hypernuclear programme at PANDA
A. Sanchez Lorente, P. Achenbach*, J. Pochodzalla, and S. Sánchez Majos

Abstract—The technical design of the PANDA experiment at the future FAIR facility next to GSI is progressing. At the proposed anti-proton storage ring the spectroscopy of double Λ hypernuclei is one of the four main topics which will be addressed by the Collaboration. The hypernuclear experiments require (i) a dedicated internal target, (ii) an active secondary target of alternating silicon and absorber material layers, (iii) high purity germanium (HPGe) detectors, and (iv) a good particle identification system for low momentum kaons. All systems need to operate in the presence of a high magnetic field and a large hadronic background. The status of the detector developments for this programme is summarized.

Index Terms—Hypernuclei, antiproton-induced reactions, design of experiments.

I. THE HYPERNUCLEAR PROGRAMME AT PANDA

HYPERNUCLEAR research will be one of the main topics addressed by the PANDA experiment at the planned Facility for Anti-proton and Ion Research (FAIR) next to the GSI site near Darmstadt. The FAIR complex will include the High Energy Storage Ring (HESR) to store antiprotons between 0.8 and 14.4 MeV energy. Intense and high quality beams with luminosities up to $10^{32}$ cm$^{-2}$s$^{-1}$ and momentum resolutions down to $10^{-6}$ are expected. The PANDA hypernuclear programme shall reveal the ΛΛ strong interaction strength, not feasible with direct scattering experiments [1], [2].

In the planned setup there exist many experimental challenges and several European research groups are working on the realization of the detectors. A detailed design will be available in the mid-term future. When reflecting upon the state of the preparations, one should be aware that the construction of the anti-proton storage ring and the PANDA experiment has not yet started.

Low momentum Ξ pairs can be produced in $p\bar{p} \rightarrow Ξ^{-}Ξ^{+}$ or $mn \rightarrow Ξ^{-}Ξ^{+}$ reactions with high rates using the anti-proton beam on an internal target. The advantage as compared to the kaon induced reaction is the fact that the anti-proton is stable and can be retained in a storage ring. This allows a rather high luminosity even with very thin primary targets.

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The authors are with the Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany. (e-mail: lorente@kph.uni-mainz.de, patrick@kph.uni-mainz.de, pochodza@kph.uni-mainz.de, sanchez@kph.uni-mainz.de)

II. HYPERNUCLEAR TARGET

The main purpose of the hypernuclear target, seen in Fig. 1, is the tracking and stopping of the produced cascade hyperons and their decay products. The active part of the secondary target was designed with silicon strip sensors of dimensions $41 \times 0.3 \times 41$ mm$^3$ in a pitch of 150 µm. The slowing down of the $Ξ^{-}$ proceeds (i) through a sequence of nuclear elastic scattering events inside the residual nucleus in which the annihilation has occurred and (ii) by energy loss during the passage through an active absorber. If decelerated to rest before decaying, the particle can be captured inside a nucleus, eventually releasing two Λ hyperons and forming a double hypernuclei. The geometry of the target is essentially determined by the lifetime of the hyperons and their stopping time in solid material. Using an event generator [3] which is based on an Intra Nuclear Cascade model and which takes as a main ingredient the rescattering of the antihyperons and hyperons, the associated Ξ will undergo annihilation 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 at PANDA a high production rate of single and double hypernuclei under unique experimental conditions will be feasible.

Fig. 1. The secondary target consisting of thin layers of silicon alternated with different absorber material of light nuclei in four segments [3], [4]. The target surrounds the anti-proton beam-pipe and must not block the trajectories of the forward going particles tagging the hypernuclear events (direction of anti-protons indicated by arrow).
PANDA is the operation of the PANDA target spectrometer is shown in Fig. 4 (right). Hyperons with high momenta will dominantly decay before being slowed down. About 500 MeV/c can be stopped prior to their free decay, Fig. 2 (bottom). The typical momenta of the stopped hyperons are in the range of 200 MeV/c. For the present simulations a target thickness of 26 mm was chosen consisting out of 30 layers of silicon strip detectors with alternating layers of absorber material, as shown in Fig. 3. The active layers provide also tracking information on the emitted weak decay products of the produced hypernuclei. The choice of the absorber material is crucial for the magnitude of the cross-section. Also the number of excited states of the core should be small and the states should be well separated. The experiment will focus on light secondary target nuclei with mass number \( A_\text{p} < 13 \). Since the identification of the double hypernuclei has to rely on the unique assignment of the detected \( \gamma \)-transitions, different enriched light isotopes (\(^9\)Be, \(^{10,11}\)B, \(^{12,13}\)C) will be used.

III. HIGH PURITY GERMANIUM ARRAY

For the high resolution spectroscopy of excited hypernuclear states a germanium \( \gamma \)-array is required. To maximize the detection efficiency the \( \gamma \)-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 \( \gamma \)-rays from the slowly moving hypernuclei are emitted rather isotropically the germanium detectors will be arranged at backward axial angles \( \theta \geq 100^\circ \). A full simulation of the hypernuclei detector’s geometry has been completed. Fig. 4 (left) shows the design of the \( \gamma \)-ray spectroscopy setup with 15 germanium cluster detectors (each comprising 3 crystals). The integration of the hypernuclear physics setup into the PANDA target spectrometer is shown in Fig. 4 (right).

At an average interaction rate of \( 5 \cdot 10^6 \text{ s}^{-1} \) UrQMD+SMM calculations of \( \bar{p}+C \) interactions at 3 GeV/c momentum predict in the backward hemisphere a total charged and neutral particle rate of \( 3.5 \cdot 10^2 \text{ s}^{-1} \). Since most of the charged particles emitted into backward axial angles are very low in kinetic energy, the majority of them will be absorbed in the beam pipe and in the signal cables coming from the silicon sensors of the secondary target. An especially critical issue are the neutrons emitted into backward axial angles.

Another major challenge at PANDA is the operation of the germanium detectors close to a strong magnetic field over long periods. These devices have been only occasionally used in such conditions and their behavior was not well known. In order to look for a quantitative answer to these two issues, an extensive R&D project has been carried out within a Joint Research Activity (HyperGamma) of the European Union Sixth Framework Programme. Two existing \( \gamma \)-ray detectors have been put inside a magnetic field up to 1.6 T: the Versatile and Efficient GAmma (VEGA) super-segmented Clover detector and the Euroball Cluster detector. The experimental results obtained so far have been summarized in Ref. 6 and it was demonstrated that the energy resolution of both detectors was nicely preserved up to 1 T.

IV. PARTICLE IDENTIFICATION

A small fiber barrel read-out by silicon photomultiplier (SiPM) has been discussed as an option for a time-of-flight
Fig. 4. Arrangement of 15 cluster detectors comprising a total of 45 HPGe crystals for hypernuclei experiments at PANDA (left) and its integration with electromechanical coolers into the target spectrometer when its end-cap and micro vertex detectors have been removed (right) [3]. The beam enters from left; the primary and secondary target are not visible.

(ToF) start detector in the hypernuclear physics programme of PANDA. The SiPM is a novel semiconductor photodetector operated in the limited Geiger mode, capable of resolving individual photons [7]. For this sub-detector system the achievable time resolution at minimum detector mass is a main issue. A SiPM is intrinsically a very fast detector with a single photoelectron time resolution of <100 ps (FWHM). When coupled to thin and short scintillating fibers the timing properties are fully dominated by the scintillation time constants and depend only on the average number of detected photons. The scintillation light from a 2 m organic fiber with double cladding has been measured by two SiPM when excited by minimum ionizing particles crossing its center. The photoelectron yield was derived from the ADC spectrum as shown in Fig. 5. On average, ∼5 pixels have fired in response to an electron crossing the fiber. The time resolution was determined by taking the time difference between the left and right signal simultaneously and was found to be FWHM = 1.4 ns. A gate on individual peaks made it possible to determine the time resolution as a function of the number of fired pixels. This study could be used to estimate possible improvements by increased light output.

A GEANT4 simulation was performed of such a TOF system: a start detector of ∼2000 scintillating fibers placed in two rings and a TOF barrel detector of 16 slabs (3 × 0.5 × 180 cm). The simulation revealed that for low momentum kaon identification the stop detector must provide a time resolution of <100 ps, whereas the fiber detector has to provide the start time with a minimum resolution of ∼400 ps. It seems challenging to achieve these values with the geometries and photon detection devices described so far.

One improvement is made by using a large area SiPM/fiber combination, and it was concluded that SiPM with 3 × 3 mm² active area can be used in combination with scintillator or radiator strips of this cross-section for fast time response measurements. Only recently, lutetium aluminum garnet (LuAG, chemical formula Al₅Lu₃O₁₂) activated by cerium became available as possible fiber material. Its density of 6.73 g/cm³ and decay time of 70 ns brings some advantages for time dependent and coincidence measurements. Primarily, the higher density compared to organic fibers results in a higher light output from the fibers. The wavelength of the emission spectrum is at 535 nm which is ideal for avalanche diode or SiPM readout. The photon yield is ∼20 000 Photons/MeV and crystals can be grown 1 mm in diameter and up to 500 mm length. We have started the research into prototypes such as fiber bundles that could be used as a TOF start detector.

Fig. 5. Measured pulse height spectrum from a SiPM/fiber setup, as being discussed as an option for the start detector of the PANDA hypernuclear programme. The position of the pedestal peak is indicated by a vertical line, the following peaks resolve the signals from single and multiple pixels of the SiPM. On average, ∼5 pixels have fired in response to an electron crossing a thin organic fiber.
V. CONCLUSIONS

In combination with the high luminosity of the anti-proton beam in HESR the PANDA experiment at FAIR will be able to explore the level scheme of double hypernuclei for the first time. The spectroscopic information on double hypernuclei will be obtained via \(\gamma\)-ray detection using HPGe detectors located near a dedicated arrangement of targets.

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