High precision $\gamma$ spectroscopy of $\Lambda\Lambda$-Hypernuclei at the PANDA experiment

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Abstract. Hypernuclear research will be one of the main topics addressed by the PANDA experiment at FAIR at Darmstadt (Germany). Thanks to the use of stored antiproton beams, copious production of double $\Lambda\Lambda$-Hypernuclei is expected at the PANDA experiment, which will enable high precision gamma spectroscopy of such nuclei for the first time. At PANDA excited states of $\Xi^{-}$ hypernuclei will be used as a starting point for the formation of double $\Lambda\Lambda$-Hypernuclei. In order to predict the yield of particle-stable double hypernuclei a microcanonical decay model was developed. For the detection of these nuclei, a devoted hypernuclear detector setup is planned. This set-up consists, in addition to the general purpose of the PANDA set-up, of a primary nuclear target for the production of $\Xi^{-}+\Xi$ pairs, a secondary active target for the hypernuclei formation and the identification of associated decay products and a germanium array detector to perform gamma spectroscopy. Moreover, one of the most challenging issues of this project is the fact that all detector systems need to operate in the presence of a high magnetic field and a large hadronic background. In these proceedings details concerning the identification procedure of double hypernuclei and the suppression of background will be presented. In addition, the current status of the activities related to the detector developments for this challenging programme will be briefly given.

1. Introduction
The simultaneous production and implementation of two $\Lambda$ particles into a nucleus is intricate. There is a possibility to produce multi-strange hypernuclei in heavy ion collisions via coalescence [1, 2]. The first observation of antihypernuclei by the STAR collaboration impressively illustrates the potential of this method [3]. However, high resolution spectroscopy of excited states is not feasible. To produce double hypernuclei in a more ‘controlled’ way the conversion of a captured $\Xi^{-}$ and a proton into two $\Lambda$ particles can be used. This process releases, ignoring binding energy effects, only 28 MeV. For light nuclei there exists, therefore, a significant probability of the order of a few percent that both $\Lambda$ hyperons are trapped in the same excited nuclear fragment [4, 5, 6, 7, 8, 9]. After an atomic cascade, the $\Xi^{-}$ hyperon is eventually captured by a secondary target nucleus and converted via the $\Xi^{-}p\rightarrow\Lambda\Lambda$ reaction into two $\Lambda$ hyperons. In a similar two-step process relatively low momentum $\Xi^{-}$ can also be produced using antiproton beams in $\bar{p}p\rightarrow\Xi^{-}\Xi^{+}$ or $\bar{p}n\rightarrow\Xi^{-}\Xi$ reactions if this reactions happens in a complex nucleus where the produced $\Xi^{-}$ can re-scatter[10, 11]. The advantage as compared to the kaon induced reaction is that antiprotons are stable and can be retained in a storage ring. This allows a rather high luminosity even with very thin primary targets. Because of the two-step mechanism, spectroscopic studies, based on two-body kinematics like in single hypernucleus production,
cannot be performed. Spectroscopic information on double hypernuclei can therefore only be obtained via their decay products. The kinetic energies of weak decay products are sensitive to the binding energies of the two Λ hyperons. While the double pionic decay of light double hypernuclei can be used as an effective experimental filter to reduce the background [11] the unique identification of hypernuclei ground states only via their pionic decay is usually hampered by the limited resolution. Instead, γ-rays emitted via the sequential decay of excited double hypernuclei may provide precise information on the level structure.

![Figure 1. Relative production probability of double hypernuclei (top part) and single hypernuclei (lower part) for an excited 10ΛΛLi nucleus as a function of its excitation energy.](image)

2. Statistical decay of excited doubly Strange Nuclei

In order to limit the number of possible transitions and thus to increase the possible signal to background ratio, the experiment will focus on light secondary target nuclei. To describe this break-up process of the excited primary ΛΛ nucleus and in order to estimate the population of individual excited states in double hypernuclei after the conversion of the Ξ−, we have developed a statistical decay model which is reminiscent of the Fermi break-up model [12]. We assume that the nucleus decays simultaneously into cold or slightly excited fragments. In the case of conventional nuclear fragments, we adopt their experimental masses in ground states, and take into account their particle-stable excited states. For single hypernuclei, we use the experimental masses and all known excited states. For double hypernuclei we apply theoretically predicted masses and excited states [13].

In the model we consider all possible break-up channels, which satisfy the mass number, hyperon number, charge, energy and momentum conservation, and take into account the
competition between these channels. Since the excitation energy of the initially produced double hypernuclei is not exactly known, we performed the calculations as a function of the binding energy $B_{\Xi}$ of the captured $\Xi^-$.

As an example Fig.1 shows excitation function of the relative production probability of double hypernuclei (top part) and single hypernuclei (lower part) for a primary $^9\Lambda\Lambda Li$. Since the conversion of the $\Xi^-$ is expected to take place close to $B_{\Xi}=0$ MeV the production of excited double hypernuclei is predicted to dominate in the PANDA experiment [14].

![Figure 1. Schematic view of the hypernuclear setup in PANDA. The picture on the left shows a side view of the hypernuclear experimental setup. The two pictures on the right show two different views of the mechanism which holds the target at a constant interaction rate by an automatic feedback system which continuously adjusts the wire positions via stepping motors. The target mechanism is mounted inside the vertex vessel, surrounded by the moveable parts of the secondary active target.](image)

3. Integration inside the PANDA spectrometer

A big challenge to be solved in order to place the hypernuclear detector setup, is the limited space available at the entrance of the PANDA spectrometer. Therefore, some modifications of the inner part of the former spectrometer is needed. In particular, due to the fact that double $\Lambda$-Hypernuclei formation proceeds in a two-steps process, a dedicated target system consisting of a primary and secondary interaction point with an associated beam line is required (see Fig. 2). Since this target system has to be placed outside the interaction region of the PANDA spectrometer, detectors such as the Micro Vertex Detector (MVD) and Backward EndCap Calorimeter will be removed to avoid unnecessary radiation damage. In addition, the central frame dedicated to hold the beam line and the central tracker detectors will also be accordingly adapted to the hypernuclear setup.

3.1. Primary target

The main role of the primary target will be the production of low momentum $\Xi$ hyperons. Although heavy targets are more efficient for re-scattering of the produced primary particles and hence for the emission of low momentum $\Xi$ hyperons, light targets will be preferred in order to avoid a high hadronic background into backward axial angles, where the germanium detectors are located. Furthermore, Coulomb scattering in heavy primary targets leads to significant losses of antiprotons. Additionally, it is required that the luminosity of the $\bar{p}$-beam remains as constant as possible. In addition, high interaction rates will be avoided by choosing an appropriate fraction of the beam halo onto the target, what can be achieved by an monitoring mechanism where the
beam as well as the target can be steered till the desired interaction rate is reached (see Fig.2). As a result, the use of thin carbon micro-ribbons [15] seems to be the best candidate to allow a stable operation over a sufficiently long measuring period.

3.2. Secondary active target

The purpose of the active volume of the secondary target is the tracking of charged particles generated during the first and the secondary interaction. As a consequence, its geometry is based on a compact structure where silicon micro-strip detectors layers are in direct contact with absorber material [16]. In analogy to the germanium detectors array, this device has to be able to operate in extreme conditions such as a large hadronic environment, since it is close to the interaction point. Furthermore, the material budget on the detector volume must be kept low. The feasibility of such a device has recently been studied in Mainz, by evaluating the influence of putting layers of absorber material directly on a silicon sensor [16]. Results have not shown any significant change on the preamplifier signal caused by the vicinity of an boron layer [16]. The sensor utilized is a double sided micro-strip detector with dimensions of $2 \times 2 \text{ cm}^2$, a strip pitch of $50 \mu\text{m}$, punch-through biasing and AC coupled contact pads. The sensor is mounted on a L-shaped PCBoard displayed in Fig.3 and is bonded to a APV25-S1 front-end chip which features 128 channels. In order to avoid a huge load of hadronic flux on the readout electronics, the use of Ultra-thin Al-Polyimide micro-cables is foreseen. The reason for that, is the routing of analog signals from silicon sensors to the readout system outside the interaction region and as a result to decrease the amount of material budget on the detecting volume. A prototype of such cables has already been manufactured in SE SRTIIE, Kharkov, Ukraine. These cables were made on the basis of adhesives less aluminum-polyimide foiled dielectrics. In addition, the PCB used for testing the analog signals, has to be modified accordingly (see Fig.3). The cable will be connected to the chip via bonding wires and to the readout electronics via a fine pitch connector. Further activities dedicated to investigate the effect of the cable length on the signal transmission are in progress. In addition, the performance of a holding structure for the whole device, is being studied. The mechanics of such a device has to be optimized considering thermal and mechanical properties of the holding structure.

4. The HPGe cluster Array

In order to increase the detection efficiency needed for a high resolution $\gamma$-Spectroscopy, the high-purity germanium (HPGe) detectors array has to be placed as close as possible to the interaction point and cover a wide solid angle. Due to the limited space of the PANDA spectrometer, the
Figure 4. HPGe triple cluster array assembled to a X-Cooler device. The encapsulated n-type coaxial HPGe crystals (EUROBALL) are arranged in a triangular form. The free space behind the crystals is foreseen for electronics. The connection of the crystal vessel to the cold head of the cooler is flexible to enable the placement of each cluster at backward axial angles. (1) encapsulated crystals, (2) flexible neck, (3) X-Cooler cold head, (4) X-Cooler Cable. The figure on the right shows the energy spectra corresponding to the 1,332 keV line of $^{60}$Co for two different cooling devices. The dashed spectrum corresponds to the case where the germanium crystal has been cooled electro-mechanically showing a slightly worsening of the energy resolution.

arrangement of the germanium detector array will only be possible at backward axial angles. That means for instance, that the operation of these detectors will have to withstand a large flux of hadronic background and a high magnetic field [17], which can influence the good energy resolution ($\sim 3$ keV at the 1,332 MeV line of $^{60}$Co) of these detectors. A possible solution for the space limitation has been to replace the standard cooling system, based on liquid nitrogen dewars, by a mechanical cooling device [18]. Fig. 4 shows a prototype for a triple germanium cluster array cooled by an electromechanical device. After installation of each of the encapsulated germanium crystals in the cryostat or vacuum vessel, the system has to reach optimum vacuum conditions to be properly operated.

The cooling efficiency of these devices has been successfully tested for three encapsulated germanium crystals without observing any additional worsening of the energy resolution [19]. Further investigations are currently taking place in Mainz at a dedicated test station. The scope of these studies is to evaluate to what extent the energy resolution of a germanium detector, cooled electro-mechanically, can be influenced. For this reason, an ORTEC GEM-75205P device and analog readout electronics has been used. The energy resolution of such a device has been measured with a $^{60}$Co source considering two different cooling devices, namely a standard liquid nitrogen dewar and a X-Cooler device. For the case of a standard cooling system, the energy resolution was found to be 1.86 KeV for 1.332 keV line. The one achieved by the X-cooler device has been 1.97 keV, which seems to be consistent. Fig. 4 shows the energy spectra corresponding to the 1,332 keV line of $^{60}$Co, obtained by considering the two cooling systems named above. The dashed spectrum corresponds to the case where the germanium crystal has been cooled electro-mechanically and although the energy resolution for this case is slightly worse, one can see that the use of the X-Cooler as a cooling option seems to be nevertheless acceptable. Further information about temperature effects and their impact on the spectroscopy properties as well as the performance of the detector and the X-Cooler assembly is in progress. In addition, activities concerning the use of digital electronics to evaluate pile-up effects, and radiation damages in a

1 The energy resolution provided by Ortec is about 2.05 keV
high flux hadronic environment are also under preparation [20].

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