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PRODUCTION OF STRANGE MESONS, HYPERONS AND HYPERNUCLEI IN Ag+Ag COLLISIONS AT $\sqrt{s_{NN}} = 2.55$ GeV MEASURED WITH HADES*

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In March 2019, the HADES experiment recorded 14 billion Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV as a part of the FAIR phase-0 physics program. In this contribution, we discuss the reconstruction and analysis of weakly decaying strange hadrons and hypernuclei emerging from these collisions. Focus is put on measuring the mean lifetimes of these particles.

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1. Introduction

In heavy-ion collisions at bombarding energies of a few GeV per nucleon as explored by HADES, the nuclear matter is compressed to densities above its ground-state density. At the same time, it is heated to temperatures of 70 MeV deduced from dielectron spectroscopy [1]. Similar densities and temperatures are also expected in merging neutron stars [2, 3]. Therefore, the study of heavy-ion collisions in the few GeV regime allows to deduce information on the microscopic composition and, ultimately, also macroscopic properties like, for example, the equation of state of astronomic objects like merging neutron stars.

1.1. Strange hadron and hypernuclei production

In this energy regime, the lightest strange mesons, the kaons, as well as the lightest hyperons, the Λ hyperons, are produced close to their free nucleon–nucleon threshold energy which results in a steep rise of their excitation function with increasing $\sqrt{s_{NN}}$ and comparably low production multiplicities $\lesssim 0.1$ per collision [4–6]. At the same time, the presence of nucleons

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from the colliding nuclei in the fireball favors the emission of light nuclei as well as hypernuclei involving one (or more) hyperons [7]. These are of extraordinary importance as their properties allow to deduce information on the underlying hyperon–nucleon interaction which is highly relevant for the equation of state at high densities [8, 9].

2. HADES experiment

The HADES experiment, which is schematically depicted in an expanded view in Fig. 1, is a multi-purpose magnet spectrometer and a fixed-target experiment operated with the SIS18 accelerator at the GSI, Darmstadt, Germany. Besides heavy-ion $A+A$ collisions, also elementary $p+A$ and $p+p$ as well as pion-induced $\pi+A$ collisions are measured, *e.g.* [10–12]. Starting from the segmented 15-fold silver target, the particles traverse a Ring-Imaging CHerenkov (RICH) detector for e^+/e^- identification, two low-mass Mini Drift Chamber (MDC) tracking stations, a toroidal magnetic field, followed by two further MDC tracking stations, and depending on the polar angle, either a Resistive Plate Chamber (RPC) or a Time-of-Flight (ToF) scintillation detector for the time-of-flight measurement. The setup is completed with an Electromagnetic CALorimeter (ECAL) for photon detection, a Forward Wall (FW) hodoscope for measurement of the event plane, and a diamond reaction time and trigger detector (START) located in front of the target. Besides the RICH, the FW, and the START detector, all detectors are splitted into six independent sectors covering almost the entire azimuthal angle. More details on the HADES experiment are given in [13, 14].

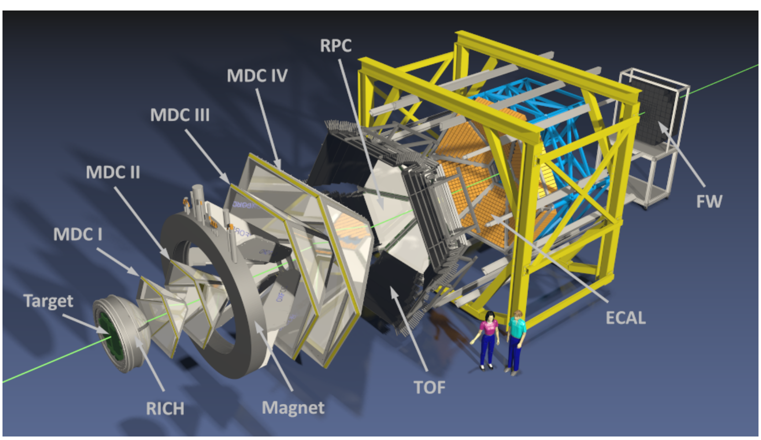

Fig. 1. Schematic expanded view of the HADES detector setup.

3. Weak decay recognition

In contrast to the charged kaons which have a mean flight length $c\tau$ of few meters and are thereby measured directly in the detectors, the Λ hyperon, K^0_{S} meson, and all known hypernuclei have a $c\tau$ of only few centimeters and thereby need to be reconstructed in HADES from their decay daughters. Due to the large amounts of protons, pions, and light nuclei not associated with weak decays, a method to effectively separate the signals from the background is required. As a result of the macroscopic $c\tau$ values of weakly decaying particles, a spatial displacement between the primary event vertex and the secondary decay vertex can be observed. This displacement results in a so-called *Off-Vertex-Decay-Topology* which is quantified using the following parameters defined in the laboratory system:

- Distance between the primary and secondary vertices;
- Distance of closest approach (DCA) between the daughter tracks and the primary vertex;
- DCA between reconstructed mother track and primary vertex;
- DCA between the two daughter tracks;
- Opening angle between the two daughter tracks.

In addition, the method proposed by Armenteros and Podolanski [15] is used to take the kinematic constraints of decays into account as described in [6, 16]. Finally, the rejection of background is enhanced further by using a Multi-Layer-Perceptron (MLP) artificial Neural Network (aNN) from the Toolkit for Multivariate Data Analysis (TMVA) [17]. Therefore, the Off-Vertex-Decay-Topology parameters except the opening angle as well as the azimuthal angle of the Armenteros–Podolanski ellipse (*cf.* [6, 16]) are used as input parameters and the aNN is trained using simulated signal samples and mixed-event background samples.

In previous analyses [5, 18], it was shown that the use of an aNN to reject background in the reconstruction of weak decays significantly improves the statistical significance of the reconstructed signals compared to pure hard-cut analyses. In total, the reconstruction method allows to reconstruct 2.45 million Λ hyperons and 1.55 million K^0_{S} mesons as shown in the invariant mass distributions in Fig. 2.

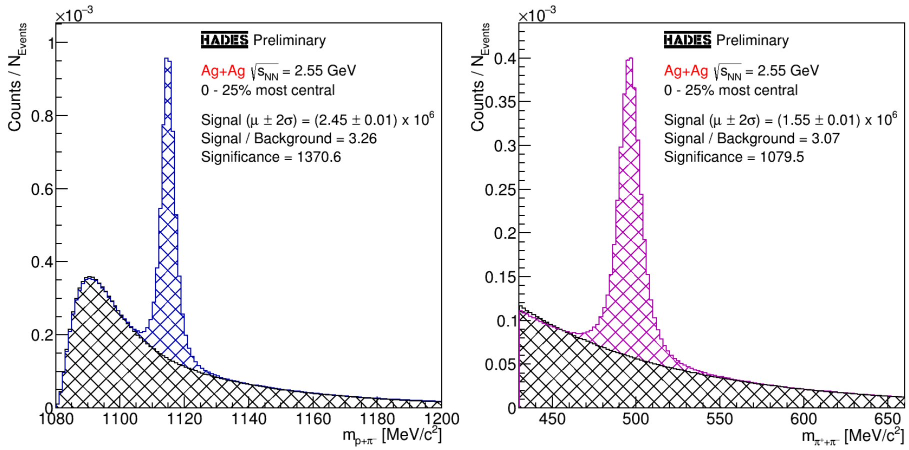

Fig. 2. Invariant mass spectra of $\Lambda \to p + \pi^-$ decays (left) and $K^0_{\rm S} \to \pi^+ + \pi^-$ decays (right) from the 0–25% most central Ag(1.58A GeV)+Ag events measured by HADES.

4. Lifetime measurements

For the goal of measuring the mean lifetimes of $^3_\Lambda$H and $^4_\Lambda$H hypernuclei, first, the method has to be assessed to exclude any systematic effects coming from *e.g.* the required correction factors for acceptance and efficiency effects. For this purpose, the lifetimes of Λ hyperons and $K^0_{\rm S}$ mesons are ideally suited, as they are measured with high precision by many experiments and independent of the production mechanism. Furthermore, their highly significant signals allow for studies with vanishing statistical fluctuations. In the following, the measurement technique of mean lifetimes is described.

The decay time t of a particle is calculated from its decay length l, its velocity β, and its Lorentz factor γ. Thereby, the reconstructed Λ hyperons are distributed to 37 equally sized intervals of 40 ps width ranging from 120 to 1600 ps, while the reconstructed $K^0_{\rm S}$ mesons are distributed to 46 equally sized intervals of 10 ps width ranging from 40 to 500 ps. For each interval, the reconstructed signals are extracted from the corresponding invariant mass spectrum in a $\pm 2\sigma$ range determined by the Gaussian fit functions.

The extracted signals are corrected for detector effects using Λ hyperons and $K^0_{\rm S}$ mesons generated according to the kinematic distributions determined in the multi-differential analyses described in [6]. For a given decay time, the kinematic distributions strongly influence the distribution of decay lengths which further influences the integrated acceptance and efficiency correction factors. Thus, proper kinematic distributions are mandatory.

Finally, the decay curves shown in figure 3 are obtained, fitted with the decay law according to equation (1) to extract the mean lifetime of Λ hyperons and $K^0_{\rm S}$ mesons

$$N\left(t\right) = N_0 \cdot \exp\left(-\frac{t}{\tau}\right) \Rightarrow \frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{N_0}{\tau} \cdot \exp\left(-\frac{t}{\tau}\right) . \qquad (1)$$

The obtained mean lifetimes τ of $(262 \pm 2 \pm 3)$ ps (Λ) and $(92 \pm 1 \pm 1)$ ps ($K^0_{\rm S}$) are both in accordance with the corresponding literature values of 263 ps and 90 ps [19]. The first given uncertainty is of statistical nature, while the second one is of systematic nature and obtained by altering selection criteria used for the identification of the corresponding decays. Since these alternative selection criteria correspond to pure hard-cut analyses, any systematic effect which might arise from using the aNN is included in the systematic uncertainties. This proves that the HADES spectrometer as well as the applied methods are suited to measure the lifetimes of weakly decaying particles.

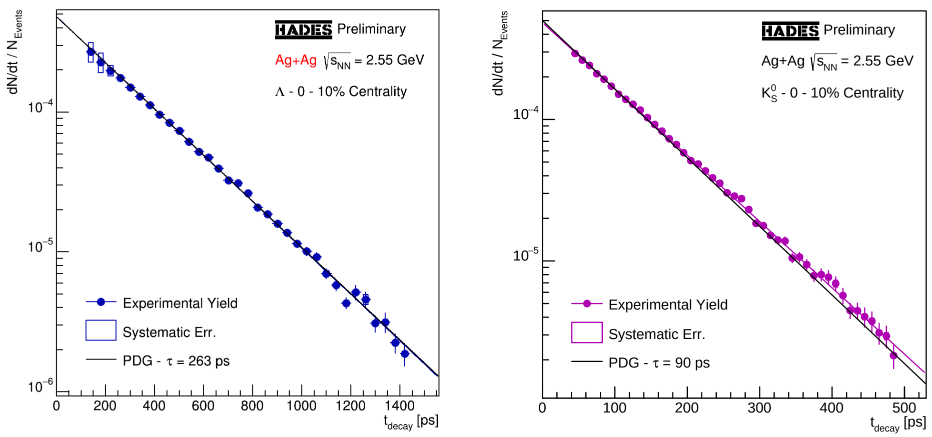

Fig. 3. (Color online) Decay curves of Λ hyperons (left) and $K^0_{\rm S}$ mesons (right) from the 0–10% most central Ag(1.58A GeV)+Ag events measured by HADES. The colored lines correspond to the exponential fit functions and the black lines to the PDG literature lifetimes [19].

5. Summary and outlook

In this contribution, we have presented benchmark measurements of Λ hyperons and $K^0_{\rm S}$ mesons demonstrating the capability of HADES for high-precision lifetime measurements of weakly decaying particles. In the next step, the lifetimes of the currently accessible hypernuclei, the $^3_\Lambda$H and the $^4_\Lambda$H, are going to be measured which might provide further constraints to models describing the highly relevant hyperon–nucleon interactions.

In parallel to the ongoing analysis of the Ag(1.58A GeV)+Ag data, the HADES Collaboration is implementing the Kalman-Filter-based KF-Particle-Finder [20] package to reconstruct decaying particles. This approach is already employed by STAR, ALICE and the CBM to increase the reconstruction efficiencies of decaying particles. Thereby, it will strongly enhance the reconstruction and analysis of hypernuclei, in particular with respect to three-body decay channels to reconstruct, for example, the ${}^{4}_{\Lambda}$He.

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