The FAIR Phase-0 Hyperon Program at HADES

Jana Rieger[1,*] for the HADES collaboration and the PANDA@HADES collaboration

[1]Department of Physics and Astronomy, Uppsala University, Lägerhyddsvägen 1, 75237 Uppsala, Sweden

Abstract. Hyperons are a unique probe to study the non-perturbative aspects of the strong interaction. At HADES, they are produced in proton or pion induced reactions at kinetic energies up to 4.5 GeV. Already in the past, HADES has shown its potential for hyperon physics, including Λ polarization, Λ-N interaction and measurements of the Λ(1405) and Λ(1520) line-shapes. The HADES detector has recently been extended with a forward detector, partly developed for the PANDA experiment, extending the acceptance for hyperon channels at forward angles. The PANDA@HADES initiative gives the opportunity for an even richer hyperon program. The current main objectives are the production of hyperon resonances, electromagnetic decays of hyperons with special focus on hyperon Dalitz decays and double strangeness production, including a $\Lambda - \Lambda$ interaction study and Ξ^- production. First results from the ongoing studies promise a successful execution of the program. In the future, there is the possibility for a pion beam experiment with HADES, enabling further hyperon studies.

1 Introduction

What is so fascinating about hyperons? - They are strange! Studying hyperons instead of "normal" matter made up from up and down quarks provides a new angle to the strong interaction. Although known for decades, some of the features of the strange hyperons Λ, Σ, Ξ and Ω, being part of the baryon spin 1/2 octet and spin 3/2 decuplet, are rather unexplored territory to this day. At the energy scale of hadron formation, the coupling of the strong interaction is strong, we have entered the non-perturbative regime where model predictions become difficult. The creation of a strange-antistrange pair requires an energy of around 200 MeV, which is close to the QCD cut-off scale where quarks form hadrons. At this scale, it is unclear what the relevant degrees of freedom are - quarks and gluons, or hadrons? Hyperons can provide new insights.

Studying the polarization of hyperons can give us hints about their production mechanism and properties of dense nuclear matter produced in heavy ion collisions. In strong and electromagnetic (i.e. parity-conserving) reactions with unpolarized beam and target, the hyperon spin can be polarized with respect to the normal of the production plane. This polarization is experimentally accessible thanks to its weak, parity violating decay in which the emission angle θ of the daughter hadron can be related to the hyperon polarization by

$$\frac{dN}{d\cos\theta} \propto (1 + \alpha P \cos\theta)\,, \tag{1}$$

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[*] e-mail: jana.rieger@physics.uu.se

where α is the hyperon decay parameter [1] and P the polarization.
Electromagnetic transition form factors (TFF) describe the q^2 dependence of the coupling of a virtual photon to a non-point-like particle. By studying hyperon TFFs, the structure of these hadrons can be probed. Usually form factors are studied in electron scattering experiments. This probes the space-like regime where $Q^2 = -q^2 > 0$ with q being the four-momentum transfer. Since hyperons are unstable, this approach is not possible. In the time-like region, TFFs can be studied, either by producing the hyperon in a collider experiment at large $-Q^2$ or by measuring the Dalitz decay where a hyperon Y^* decays into a lighter hyperon Y and an electron-positron pair. This makes TFFs at small $-Q^2$ accessible which can be continuously extended to the physical space-like region. The possibilities for measuring TFFs are illustrated in Figure 1. Measurements of hyperon-hyperon TFFs are highly requested from theory. E.g. the $\Sigma^0 - \Lambda$ TFF is necessary to measure the Σ^0's magnetisation radius using dispersion relations where the behaviour of the space-like TFF can be obtained from the time-like one [2] and the differential decay width of the Dalitz decays of hyperon resonances depends on the form factor, i.e. the structure of the hyperon [3].

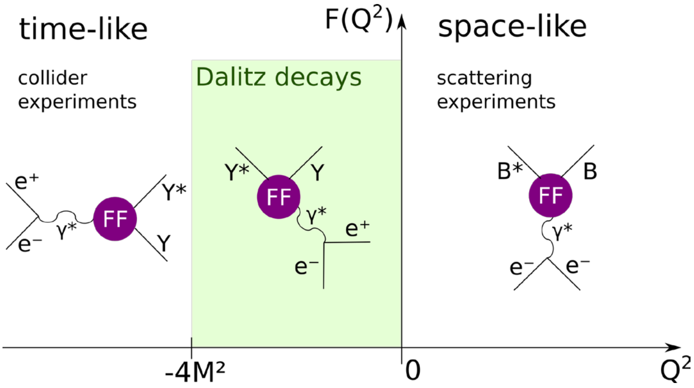

Figure 1. Three possibilities for measuring electromagnetic TFFs. In the time-like regime in collider experiments or via the Dalitz decay, in the space-like regime through scattering experiments.

Hyperons are not only produced in particle collisions in the lab but are also expected to play a crucial role in astrophysical objects such as neutron stars. Neutron stars are very dense objects, so dense that the pressure in the core should be high enough to produce hyperons which would be energetically favorable over only allowing for nucleons and electrons. However, this would lower the repulsive force arising from the Pauli principle, leading to a shift in the equilibrium between gravitation and inner pressure, which cannot describe the heaviest neutron stars that have been observed. This contradiction is called the hyperon puzzle [4]. An additional repulsive force originating from the hyperon-hyperon interaction could push the onset of hyperons to larger densities and resolve this contradiction. The hyperon-hyperon interaction can be studied using the femtoscopy method, i.e. measuring the correlation

$$C(\mathbf{p}_1, \mathbf{p}_2) := \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1)P(\mathbf{p}_2)} = \int d^3 r S_P(r) |\phi(r, \mathbf{k})|^2, \tag{2}$$

with $P(\mathbf{p}_1, \mathbf{p}_2)$ the probability of measuring $\mathbf{p}_1$ and $\mathbf{p}_2$ simultaneously and $P(\mathbf{p}_1)P(\mathbf{p}_2)$ the probability of measuring $\mathbf{p}_1$ and $\mathbf{p}_2$ independently. This is related to the source size $S_P(r)$ and the wave function $\phi(r, \mathbf{k})$. If the source size is known, the interaction can be deduced.

2 HADES

The High Acceptance Di-Electron Spectrometer HADES [5] is located at GSI in Darmstadt, Germany. It is a fixed target experiment, being served with a proton, heavy-ion or pion beam by the SIS 18 synchrotron [6, 7]. The spectrometer has undergone continuous upgrades during the past years. In the original configuration, HADES consisted of the Ring Imaging CHerenkov detector (RICH) for electron-hadron discrimination, the Multiwire Drift Chambers (MDC) for tracking and momentum reconstruction and time of flight detectors in the back. A magnet, producing a toroidal magnetic field is placed in between the MDC planes II and III.

In 2018, the RICH detector was upgraded and since 2017, the Electromagnetic CALorimeter (ECAL) has been added part by part. In addition, a series of new detectors was added in 2021 for the hyperon program [8]. This includes a new START detector to provide the event start time in front of the target and the inner Time Of Flight detector (iTOF) in front of the first MDC plane to improve the time of flight measurement and for trigger purposes. Moreover, the Forward Detector was installed, consisting of two Straw Tube tracking Stations (STS), designed and built for the PANDA experiment, and the forward Resistive Plate Chambers (fRPC) for time of flight measurement in forward direction. The Forward Detector covers polar angles from $1^\circ - 6^\circ$ and largely extends the acceptance for hyperon channels where one proton is likely to be emitted at forward angles. A schematic drawing of the PANDA@HADES setup is shown in Figure 2.

The SIS18 synchrotron has been upgraded as well in order to serve as a pre-accelerator for FAIR in the future and is now providing proton beams up to $T = 4.5\,\mathrm{GeV}$.

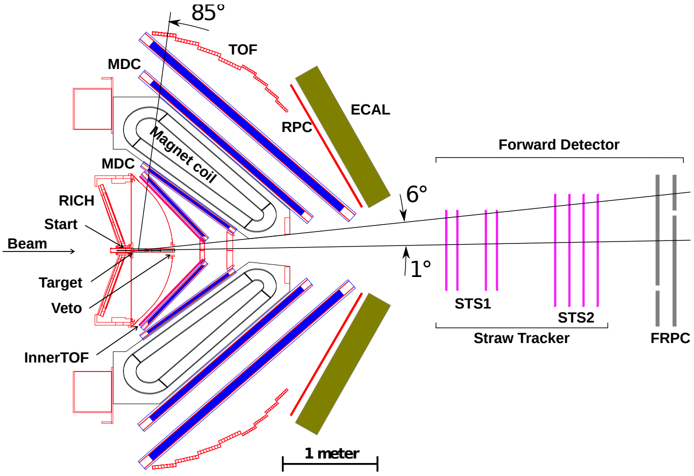

Figure 2. Schematic drawing of HADES with the hyperon upgrade. [8]

3 Hyperons in the Past

HADES has previously successfully performed a number of hyperon studies with proton induced reactions. In particular the p+Nb data has been studied intensively while elementary p+p reactions have been studied for reference. This data was taken at $T = 3.5\,\mathrm{GeV}$.

3.1 Λ polarization in p+Nb

Studying hyperon production and propagation on nucleon-nucleus collisions is an important step to understand strangeness production in heavy ion collisions. Especially the hyperon polarization is of interest since even though it is established experimentally, its origin is not yet well understood. Various models try to explain it by either quark or meson exchange but fail to describe all the data [9]. Λ polarization has been studied by HADES in p+Nb reactions [10]. The polarization was measured in dependence of transverse momentum and rapidity. The total polarization was determined to be $< P >= -0.119 \pm 0.005 \pm 0.016$, showing surprisingly that the Λ spin orientation could be preserved while traveling through nuclear medium. Λ polarization studied in Au-Au and Ag-Ag collisions [11] could give insights in how the high orbital momentum present in heavy-ion collisions is transferred to the vorticity of the matter.

3.2 Λ-N interaction in p+Nb

An additional repulsive force in the Λ-nucleon or $\Lambda - \Lambda$ interaction could help resolving the neutron star hyperon puzzle. HADES studied for the first time p-Λ correlations in p+Nb by applying the femtoscopy method [12]. It showed that for a larger data set where the statistical uncertainty is sufficiently small, this procedure allows to extract scattering lengths and effective ranges of the interaction if the source size is known. A similar study, measuring p-Λ correlations in Ag+Ag reactions with HADES, is ongoing [13].

4 Hyperons NOW

The recent HADES upgrades alongside with the upgrades of the SIS18 as a preparation for FAIR opened up the doors for an extended hyperon program. During a full month of beam-time, data were collected from p+p reactions at a kinetic energy of 4.5 GeV. These data are currently being analyzed. A total integrated luminosity of $6\,\mathrm{pb}^{-1}$ was achieved which is 60 times more than the full p+p data samples collected at 3.5 GeV.

4.1 Excited hyperons

The $\Lambda(1520)$ hyperon, a rather narrow hyperon resonance with $\Gamma = 15.6\,\mathrm{MeV}$, having negative parity and spin 3/2 [1], can be produced in nuclear medium as well as in elementary nucleon-nucleon reactions in HADES. In consequence it is predicted that its properties change in nuclear matter due to in-medium modifications of baryon-meson loops [14]. HADES has performed an inclusive analysis of the decay $\Lambda(1520) \to \Lambda\pi^+\pi^-$ in p+Nb as well as in p+p [15] and a study of the production of $\Sigma^+(1385)$ and $\Lambda(1520)$ and their hadronic decays in the new data is ongoing at the moment. The hadronic decays will in addition serve as a reference measurement for the Dalitz decays of those hyperons.
Another hyperon state of controversial structure is $\Lambda(1405)$ whose line shape in all $\Sigma\pi$ charge states is under investigation. With the new HADES data a significant increase of statistics w.r.t the former measurement [16] is expected. HADES aims at performing a line-shape measurement, making use of the neutral decay $\Lambda(1405) \to \Sigma^0\pi^0 \to p\pi^-3\gamma$. This could help to explain the double-pole structure of the $\Lambda(1405)$ hyperon [17]. The neutral decay channel excludes a contribution from the $\Sigma(1385)$ hyperon which is very close in mass, allowing for a pure measurement of the $\Lambda(1405)$ line shape.

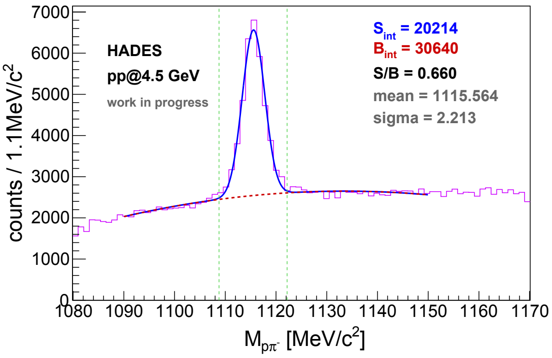

Figure 3. Invariant mass of p and π^- selected from events that contain at least two lepton tracks in addition.

4.2 Hyperon Dalitz Decays

HADES has the unique opportunity to measure for the first time electromagnetic hyperon Dalitz decays. Designed as a di-electron spectrometer, HADES is capable of detecting both, the leptons as well as the hadrons from the decaying hyperon. The first step is to measure the Dalitz decay of the Σ^0, the lightest hyperon that can decay electromagnetically. The branching ratio is predicted to be BR $= 5 \cdot 10^{-3}$ [1] but was never measured. The ongoing analysis of the data collected in 2022 shows promising first results. In Figure 3, a distinct peak at the Λ mass can be discerned in the $p\pi^-$ invariant mass spectrum where these particles were detected together with a lepton pair in the same event. Thanks to the installation of an electromagnetic calorimeter, HADES is able to measure the well-known radiative decay $\Sigma^0 \rightarrow \Lambda\gamma$ as a reference. This will lay the foundation for future measurements of the magnetic Σ^0 to Λ transition form factor. For this the dependence on the e^+e^- invariant mass is needed.

Furthermore, heavier hyperons like the $\Sigma(1385)$ and $\Lambda(1520)$ are decaying electromagnetically but with a smaller branching ratio. A feasibility study [8] shows that a measurement of the $\Sigma(1385)$ and $\Lambda(1520)$ hyperon Dalitz decays could be possible with an integrated luminosity of $15\,\mathrm{pb}^{-1}$. By analyzing the present $p + p$ data, collected at 4.5 GeV with HADES, the aim is to provide upper limits for the Dalitz decays of $\Sigma(1385)$ and $\Lambda(1520)$ and prepare for future measurements with larger luminosity.

4.3 Double Strangeness Production

Correlation studies of hyperons can give insights about double hyper nuclei, the constellation of neutron star cores and the production mechanism of the Ξ^- hyperon. The $p + p$ data at 4.5 GeV is just above the production threshold for two Λ hyperons. HADES aims at a measurement of the cross section for double Λ production in $p + p$ interactions as well as a correlation study of $\Lambda - \Lambda$ using the femtoscopy method. A feasibility study [8] shows promising results.

The Ξ^- hyperon is the lightest baryon containing two strange quarks. HADES has already performed a measurement of Ξ^- production in Ar+KCl and p+Nb [18, 19], at energies below the production threshold in free space. In both cases a large excess of the Ξ^- yield was observed compared to transport models which could be explained by feed down from resonances. A measurement of the Ξ^- production cross section and a spectroscopic study could give clarity over the production mechanism. A feasibility study [8] shows promising results.

5 Hyperons in the Future

The HADES hyperon program will continue in the future, possibly with another π beam campaign.

5.1 Possibilities of a π beam experiment

HADES at SIS18 has the unique possibility to perform experiments with a π beam, combined with a di-electron spectrometer, now with a center of mass energy of $\sqrt{s} = 1.7\,\mathrm{GeV}/c^2$. This would be a successor of the experiment performed at $\sqrt{s} = 1.5\,\mathrm{GeV}/c^2$ in 2014. The study of $\pi + p$ interactions opens many doors [20], for example the investigation of baryon-meson couplings, time-like electromagnetic transition form factors of e.g. $N^* - N$ [21] and cold nuclear matter studies of vector mesons.

6 Conclusion

By combining the excellent di-electron tagging capability with new dedicated tracking detectors for hyperon reconstruction, HADES has launched a unique hyperon physics program within FAIR Phase 0. A large $p + p$ data sample has already been collected at 4.5 GeV. The analysis of the data will partly be a continuation of studies performed in the past at a different energy but the increased luminosity and energy also open new doors into unknown terrain like hyperon electromagnetic Dalitz decays and $\Lambda - \Lambda$ correlation studies. First results from the ongoing analyses promise a successful execution of the current hyperon program. We can expect that this will not be HADES' last word about hyperons. The most prominent example is the π beam campaign that increases the scientific potential substantially.

References

[1] R. L. Workman *et al.* [Particle Data Group], PTEP **2022**, 083C01 (2022)
[2] C. Granados, S. Leupold, E. Perotti, Eur. Phys. J. A **53**, 117 (2017)
[3] N. Salone, S. Leupold, Eur. Phys. J. A **57**, 183 (2021)
[4] D. Chatterjee, I. Vidaña, Eur. Phys. J. A **52**, 29 (2016)
[5] G. Agakichiev *et al.* (HADES Collaboration), Eur. Phys. J. A **41**, 243–277 (2009)
[6] L. Dahl *et al.*, Proceedings of HIAT 2012, 211-216 (2012)
[7] J. Adamczewski-Musch *et al.* (HADES Collaboration), Eur. Phys. J. A **53**, 188 (2017)
[8] J. Adamczewski-Musch *et al.* (HADES Collaboration), Eur. Phys. J. A **57**, 138 (2021)
[9] J. Felix, Mod. Phys. Lett. **14**, 827 (1999)
[10] G. Agakichiev *et al.* (HADES Collaboration), Eur. Phys. J. A **50**, 81 (2014)
[11] R. Abou Yassine *et al.* (HADES Collaboration), Phys. Lett. **835**, 137506 (2022)
[12] J. Adamczewski-Musch *et al.* (HADES Collaboration), Phys. Rev. C **94**, 025201 (2016)
[13] N. Rathod, EPJ Web of Conferences **?**, ? (2023)
[14] M. Kaskulov and E. Oset, Phys. Rev. C **73**, 045213 (2006)
[15] K. Sumara, EPJ Web of Conferences **?**, ? (2023)
[16] J. Siebenson and L. Fabbietti, Phys. Rev. C **88**, 055201 (2013)
[17] T. Hyodo and D. Jido, Progress in Particle and Nuclear Physics **67**, 55-98 (2012)
[18] G. Agakishiev *et al.* (HADES Collaboration), Phys. Rev. Lett. **103**, 132301 (2009)
[19] G. Agakishiev *et al.* (HADES Collaboration), Phys. Rev. Lett. **114**, 212301 (2015)
[20] I. Ciepal, EPJ Web of Conferences **?**, ? (2023)
[21] D. An, EPJ Web of Conferences **?**, ? (2023)