Strangeness production measured with HADES

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Abstract. HADES is a multi-purpose, charged-particle detector operated at the SIS18 synchrotron located at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany. The provided ion beam energies of 1-2 A GeV are among the lowest of all currently running heavy-ion experiments and result in the highest baryon net-densities at freeze-out in case of Au+Au collisions. At a beam energy of 1.23 A GeV, particles containing strangeness are produced below the quasi-free NN threshold energy. Since the missing energy has to be provided by the collision system, the investigation of the production of strangeness at such energies is a very promising probe of the created medium. The data sample measured with HADES includes multi-differential analysis of charged and neutral kaons, φ mesons and Λ hyperons. We present the analysis method and the results.

1. Introduction
The properties of strongly interacting nuclear matter is crucial to our understanding of stellar objects like neutron stars. At the high temperature and low baryon net-density edge of the phase diagram we are able to perform exact QCD calculations with the help of lattice QCD [1]. However, there is still no way to perform these calculations for matter with high baryon net-densities [2] as it is expected in neutron star mergers [3]. Thus, to describe the properties of such matter, one has to rely on effective approaches that need to be tested with experimental data.

1.1. Heavy ion collisions at SIS18 energies
The only way to access matter at extreme temperatures or baryon net-densities in the laboratory are collisions of heavy ions. In the collision area, a very hot system of strongly interacting matter, i.e. fireball, is created. During the expansion of the fireball, interactions of the contained particles are ceasing, i.e. freeze-out. At center of mass energies of a few TeV, as measured at the LHC, systems with high temperatures but vanishing baryon net-densities at freeze-out, are created. Rather moderate center of mass energies of a few GeV, as measured at the SIS18, result in systems with moderate temperatures and high baryon net-densities. Very similar conditions are expected in neutron star mergers [3].

At these moderate center of mass energies, the energy available in isolated NN collisions ($\sqrt{s_{NN}}$) can be slightly below the kinematic threshold of the most probable reaction channel producing strangeness. Nevertheless, particles containing strangeness can be produced if the production process is not a pure superposition of quasi-free NN-collisions. Such effects, possible thanks to the participation of several nucleons, are in the following referred to as medium effects.
Therefore, the production of strangeness is an important observable to investigate the medium properties of the systems created at SIS18 energies.

1.2. Strangeness production below quasi-free NN threshold

In Au+Au fixed target collisions at a beam energy of 1.23 A GeV, the $\sqrt{s_{NN}}$ amounts to 2.4 GeV while the energetic threshold of the most probable reaction channel producing strangeness ($N + N \rightarrow \Lambda + K + N$) amounts to 2.6 GeV. Hence, all particles containing strangeness are produced below the quasi-free NN threshold energy in Au(1.23 A GeV)+Au collisions and are thereby called sub-threshold.

Due to the gap between the available energy in quasi-free NN collisions and the kinematic threshold of the reaction channel producing strangeness, the production of strangeness is a rather rare event. Approximately, it occurs only every 100\textsuperscript{th} event, hence high reconstruction efficiencies and large data samples are required to perform a multi-differential analysis.

2. The HADES experiment

The HADES (High Acceptance DiElectron Spectrometer) experiment is a fixed-target, heavy-ion collision experiment located at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany. It was designed to measure rare di-electron events which requires high read-out rate, low material budget and precise particle identification. HADES comprises a six-coil toroidal magnet centered around the beam axis and six identical detection sections located between the coils, covering almost the full azimuthal angle. Each sector is equipped with a Ring-Imaging Cherenkov (RICH) detector followed by low-mass Mini-Drift Chambers (MDCs), two in front of and two behind the magnetic field, as well as a scintillator hodoscope (TOF) and a resistive plate chamber (RPC) at the end of the system. The RICH detector is used mainly for electron/positron identification, the MDCs are the main tracking detectors, while the TOF and RPC are used for time-of-flight measurements in combination with a diamond start detector located in front of a 15-folded segmented target. The setup is completed by a forward hodoscope used for reaction plane determination. A detailed description of the HADES detector is given in Ref. [4].

3. Analysis of Strangeness Production

The most abundantly produced particle carrying strangeness at SIS18 energies are $\Lambda$ hyperons and kaons. Since charged kaons have a decay length $c\tau$ of several meters, they can be measured directly in the detector. This is in contrast to $\Lambda$ hyperons and $K^0_S$ mesons, having decay lengths of only a few centimeters. Therefore, they decay in front of the detector, mainly into a proton and a negatively charged pion ($\Lambda$) or into two oppositely charged pions ($K^0_S$).

The invariant mass distributions of the $p\pi^-$ and $\pi^+\pi^-$ systems enable extraction of $\Lambda$ and $K^0_S$ candidates. However the data contain a lot of background. Since protons and pions are produced several orders of magnitude more abundantly than strange hadrons, a method to suppress the background is required.
3.1. Reconstruction of Weakly Decaying Particles

Since weakly decaying strange particles travel a measurable distance before decaying, their daughter particles can be distinguished from particles originating from the primary production vertex. We quantify these criteria the following way [5]:

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

This so called Off-Vertex-Topology allows for a strong suppression of the background, yet a significant amount of signal is lost. To enhance the reconstruction efficiencies while keeping the background contamination low an artificial neural network (ANN) is used. The ANN is trained using reconstructed particles from Monte-Carlo simulations as signal sample and combinations of daughter tracks from different events as background sample. Several different multi-variant analysis approaches, contained in the TMVA package [6], were tested and evaluated based on their performance. A Multi Layer Perceptron (MLP) ANN with two hidden layers with 8 and 6 neurons is one of the best performing implementations while keeping the amount of free parameters relatively low which reduces the risk of training on statistical fluctuations.

Due to the exponential progression of the decays, most particles still decay close to the primary event vertex. As a consequence, there is a danger in training the neural network mostly on decays close to the primary vertex, for which the parameters have only low discrimination power. Therefore, the training samples are restricted to actual displaced vertex decays by applying hard cuts on the topology parameter.

![Figure 2: MVA Response distributions for the signal (green) and the background (red) training sample. The distributions are normalized to the same integral.](image)

![Figure 3: Λ₀ transverse mass spectra for 0-40% most central events. Each individual spectrum shows one rapidity bin and is scaled by a factor 10^x for better visibility. The blue spectra are the results of pure cuts while the red spectra include the MVA. [5, 7].](image)
A very clear separation between the two distributions can be observed with only 12% of all samples being classified wrongly using a cut on the MVA response at 50%.

A performance test using real data shows that the ANN performs extraordinarily well at separating signal and background. To quantify the signal quality, the significance defined by Equation 1, where S represents the amount of signal counts and B the amount of background counts in the signal region, is used. By using the ANN alongside with the standard Off-Vertex-Topology cuts, the significance of the Λ signal could be increased from 188 [5] to 425 [7]. The significance of the $K_S^0$ signal increased from 265 [5] to 364 [7]. This improvement allows to measure production rates in a larger part of the phase space. Figure 3 shows the phase space coverage with and without using the MVA in red and blue, respectively. In the next step, the reconstructed signals are used to extract information on the production of strangeness in HICs [7].

$$\text{Significance} = \frac{S}{\sqrt{S + B}}$$

3.2. Multi Differential Analysis

To extract the yield over the full phase space and to gain information on the production of strangeness, a multi differential analysis is performed. Therefore, the full data set is being divided according to centrality, which corresponds to the amount of nucleons participating in the reaction. Furthermore, it is divided according to the transverse momentum of the reconstructed particles and their rapidity, which is a Lorentz-invariant quantity for the longitudinal momentum. The yield is extracted for each sub-interval and is corrected for acceptance and efficiency using Monte Carlo simulations. The transverse mass spectrum for each centrality and rapidity is then fitted assuming a Boltzmann-distribution. These spectra are shown in Figure 3 for Λ hyperons from 0-40 most central events. The full yield in each interval of centrality and rapidity is calculated by integrating the transverse mass spectra and extrapolating them using the fit function. Finally, the extrapolation in the longitudinal direction is based on a Gaussian function, which gives the yield over the full phase space for each centrality class. More details on the multi differential analysis can be found in Ref. [8].

4. Results

In addition to Λ and $K_S^0$, also $K^+$, $K^-$ and φ are analyzed in Ref. [9]. All the particles containing strangeness are produced below their quasi-free NN threshold energy which requires additional energy to be provided by the produced system. Therefore, one expects their production rates to scale with the size of the system. In a naive picture, the size, or volume, scales linearly with the mean number of nucleons participating in the reaction $\langle A_{Part} \rangle$. Since this amount is equal to the amount of nucleons in the overlap region of the colliding nuclei, it corresponds to the centrality of the collision.

Figure 4 shows the production rates of Λ hyperons, kaons and φ mesons measured with HADES in Au+Au collisions as a function of the mean number of participants $\text{Mult}/\langle A_{Part} \rangle$. All hadron yields are fitted simultaneously with a function of the form $\text{Mult} \propto \langle A_{Part} \rangle^\alpha$ with the result: $\alpha = 1.45 \pm 0.06$ [8, 9, 10].
of participating nuclei $\langle A_{\text{Part}} \rangle$. An exponential scaling with the exponent $\alpha$ is assumed ($\text{Mult} \propto \langle A_{\text{Part}} \rangle^\alpha$). Under the assumption that the system provides the energy in sequential NN collisions, the scaling of $\Lambda$ hyperons, $K^0_S$ and $K^+$ with an energy gap between the required energy and $\sqrt{s_{NN}}$ of $\approx 150$ MeV would have to be significantly different than the scaling of $K^-$ with an energy gap of $\approx 450$ MeV or $\phi$ mesons with an energy gap of $\approx 490$ MeV. Instead, it shows that the scaling of all five particles can be described by one universal scaling parameter of $\alpha = 1.4 \pm 0.06$ as displayed in Figure 4. This indicates that the way the energy is provided by the system is more coherent than a simple accumulation in isolated NN collisions. In this picture, strangeness is produced in proportion to the size of the fireball and only redistributed statistically over the different hadrons at freeze-out [11].

5. Summary and Outlook
To summarize, our work has shown that artificial neural networks are a great tool to improve the reconstruction of weakly decaying particles. In combination with the large data samples from the HADES Au+Au campaign, it allows to reconstruct a large data sample of weakly decaying particles containing strangeness produced below their quasi-free NN threshold energy. This provides the possibility of a very detailed analysis with a special emphasis on how the required additional energy is provided by the system. Together with the results from the $K^+$, $K^-$ and $\phi$ analysis, it shows that the scaling of the production rates with the mean number of participating nuclei $\langle A_{\text{Part}} \rangle$ does not depend on the energy gap between the required energy and $\sqrt{s_{NN}}$. This points to a coherent production of strangeness below the quasi-free NN threshold. However, further investigations are required.

In March 2019, the HADES experiment conducted a four-week beamtime measuring Ag+Ag collisions at a beam energy of 1.58 A GeV. The $\sqrt{s_{NN}}$ amounts to 2.55 GeV, which is equal to the threshold energy of the production of $\Lambda$ hyperons, $K^0_S$ and $K^+$ mesons. Already in the first stage of calibration, 2.1 million $\Lambda$ hyperons and 1.2 million $K^0_S$ mesons can be reconstructed from the collected data. These large data samples will allow for a very detailed analysis of the production of strangeness, providing an independent cross check of the results and the interpretation from the Au+Au data in a different collision system.

Furthermore, Ag+Ag collisions at a beam energy of 1.23 A GeV were measured. Since this beam energy coincides with that of the Au+Au campaign, these data will allow to study the effects of the different system size independently from effects of the different beam energy in a very systematic way.

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