Sub-threshold production of $K^0$ mesons and $\Lambda$ hyperons in Au(1.23A GeV)+Au

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We present first data on sub-threshold production of $K^0$ mesons and $\Lambda$ hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV. We observe an universal $\langle A_{\text{part}} \rangle$ scaling of hadrons containing strangeness, independent of their corresponding production thresholds. Comparing the yields, their $\langle A_{\text{part}} \rangle$ scaling, and the shapes of the rapidity and the $p_t$ spectra to state-of-the-art transport model (UrQMD, HSD, IQMD) predictions. We find that none of them can simultaneously describe these observables with reasonable $\chi^2$ values.

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Relativistic heavy-ion collisions (HICs) provide a unique opportunity to study matter at 2-3 times nuclear ground state density (similar as expected for neutron star mergers [1,2]) in the laboratory. In particular, kaons and $\Lambda$ hyperons are promising probes with relevance for various astrophysical processes [3,8]. However, HICs are highly dynamical processes and therefore it is difficult to directly address fundamental aspects. Numerous works
investigated kaon production in HICs in the few-GeV energy regime in the past. Comparisons of experimental data (spectra and flow anisotropies) to transport model calculations seem to confirm a repulsive K-N potential [9,12,14–17], which has been predicted by various effective approaches [18,21]. Furthermore, constraints for the equation-of-state (EOS) of nuclear matter have been deduced from kaon production, under the assumption of energy accumulation in sequential nucleon-nucleon collisions, e.g. NN → ΔN [22,24].

Data on Λ production from HICs at low energies are scarce. At SIS18 energies only data from small collision systems are available [25,26]. While the Δ-nucleon potential is known to be attractive at ground state densities from hypernuclei formation [27], its density dependence therefore still remains vague [28].

In this paper, we report the first observation of K⁰ and Λ hyperons emitted from central Au+Au collisions at √sNN = 2.4 GeV. Both kaons and Λ hyperons are produced about 150 MeV below their free NN-threshold and hence are sensitive to the energy dissipation in the collision system. We compare the scaling of the multiplicities as function of the centrality of the collisions to the previously published data on charged kaons and φ mesons [29] and the spectra and rapidity distributions to predictions from three state-of-the-art microscopic transport models (UrQMD, HSD, IQMD) [30–32]. Based on this we discuss the validity of the previously drawn conclusions about the K-N potential and the energy dissipation during the collision in light of the new data.

The data have been collected with HADES, located at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany. HADES is a charged-particle detector consisting of a 6-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 detector (RICH) followed by 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 a forward hodoscope used for event plane determination is located. 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 the 15-fold segmented target. The trigger is based on the hit multiplicity in the TOF covering a polar angle range between 45° and 85°. A detailed description of the HADES detector is given in [33]. In total, 2.2 × 10⁸ Au+Au events are used in the present analysis corresponding to the 40% most central events. The latter is estimated based on studies using a Glauber model [34].

K⁰ mesons are identified via their decay to π⁺ and π⁻ (BR = 69.2%, ct = 2.68 cm). Λ hyperons are identified through their decay to p and π⁻ (BR = 63.9%, ct = 7.89 cm). Note that the reconstructed Λ yield contains also a contribution from the (slightly heavier) Σ⁰ baryon decaying electromagnetically exclusively into a Λ and a photon. This decay process can not be detected with the present experimental setup; hence, the Λ yield has to be understood as that of Λ+Σ⁰ throughout the paper. Pion and proton candidates used for the invariant mass analysis are identified by the curvature of their track in the magnetic field, a very loose cut on the reconstructed particle mass, and a careful track selection based on several quality parameters delivered by a Runge-Kutta tracking algorithm.

FIG. 1: Examples of K⁰ (left) and Λ (right) signals for 0–40% most central events, over mixed-event background for the bin −0.05 < y_{cm} < 0.05 and reduced transverse masses between 80–120 MeV/c² and 100–150 MeV/c², respectively.
each phase space cell for acceptance and efficiency using Monte-Carlo simulations based on Geant and a detailed description of the detector response, exposed to exactly the same reconstruction and analysis steps as the experimental data. As input for the simulation, thermal distributions of K° and Λ hyperons with an inverse slope of 90 MeV were embedded into the experimental data. The combined correction factors for the efficiency and acceptance correspond to about 50 for K° and about 100 for Λ hyperons at mid-rapidity, including the branching ratio to the π⁺π⁻ and π⁻p final state, respectively. In order to suppress the larger combinatorial background in the p⁺π⁻ sample, more stringent cuts on the decay topology were applied than in case of the π⁺π⁻ sample, resulting in the lower detection efficiencies for the Λ compared to the K° [35, 37].

The acceptance and efficiency corrected distributions of reduced transverse mass spectra for subsequent slices of rapidity for K° and Λ hyperons are presented in Fig. 2. Displayed is the number of counts per event, per transverse mass and per unit in rapidity, divided by mT. This representation is chosen to ease a comparison with single slope Boltzmann fits to the resulting distribution according to

$$\frac{1}{m_T^2} \frac{d^2N}{dm_Tdy_{cm}} = C(y_{cm}) \exp \left( - \frac{(m_T - m_0)^2}{T_B(y_{cm})} \right),$$

which describe the spectra satisfactorily. The rapidity distributions, shown in Fig. 3, are obtained by integrating the data as function of the transverse momentum pT and using Boltzmann fit functions for extrapolations in the not covered pT regions. The systematic errors of the yields in each rapidity bin are due to the variations of topology cuts, the normalization region of the mixed-event background and by the comparison of the spectra measured in the forward and backward hemisphere. The decay length distributions of the two hadrons are determined to ensure the quality of the correction procedure. We observe lifetimes in agreement with the PDG values, i.e. K°: τexp = 87.1 ± 1.1 ps, τPDG = 89.6 ± 1.6 ps; Λ: τexp = 255 ± 7 ps, τPDG = 263 ± 2 ps [38].

Multiplicity is obtained by integrating the rapidity distribution and using a Gaussian fit for extrapolation to full phase space, see dotted curve in Fig. 3. The statistical error is taken from the fit directly. The systematic uncertainty of the extrapolation is estimated based on variation within the systematic errors and using in addition to the Gaussian fit the rapidity distributions obtained from the three different transport models for extrapolation, as described below.

We obtain a total multiplicity of (1.56 ± 0.03stat ± 0.12sys) x 10⁻² K° and (4.72 ± 0.06stat ± 0.75sys) x 10⁻² Λ.

The extracted inverse slope parameters obtained from the Boltzmann fits to the mT spectra for each rapidity interval are fitted using the ansatz $T_B = \frac{T_{eff}}{\cosh(y_{cm})}$ in order to obtain the effective inverse slope T_{eff}. As the inverse slope contains a contribution from the velocity of the radial expansion of the fireball, which is proportional to the particle mass, one expects a larger inverse slope for the Λ hyperons. We find T_{eff} = 93 ± 1 ± 4 MeV for the K° and T_{eff} = 98 ± 1 ± 4 for the Λ hyperons, suggesting no strong difference between radial flow of the K° and Λ hyperons.

In addition, the analysis procedure is repeated in the same way for four centrality classes. These classes correspond to 10% steps in centrality, which can be translated into the average number of participants $\langle A_{part} \rangle$ [34]. The results are summarized in Tab. 1.

A comparison to the world data is presented in Fig. 4, where the mid-rapidity yields for central Au+Au (Pb+Pb) collisions as function of $\sqrt{s_{NN}}$ are displayed. While only experimental data on K° production exists for central HICs at energies $\sqrt{s_{NN}} > 17.2$ GeV [39, 42].
The steep energy excitation function for strange hadron (as discussed in the introduction) in combination with energy accumulates in sequential nucleon-nucleon collisions from first chance NN collisions. If one assumes that the strength of this rise characterizes the amount of 

\[ \phi \text{ in Fig. 5 and include also the multiplicities of charged particles Mult/\langle A_{\text{part}} \rangle \] as a function of \( A_{\text{part}} \), as shown in Fig. 5 and include also the multiplicities of charged kaons and \( \phi \) mesons measured in the same collision system [29]. If final state interactions play a minor role, the strength of this rise characterizes the amount of surplus energy provided by the system, over the contribution from first chance NN collisions. If one assumes that energy accumulates in sequential nucleon-nucleon collisions (as discussed in the introduction) in combination with the steep energy excitation function for strange hadron production, one expects to observe significantly different slopes, due to the clear hierarchy in the production thresholds, \( \approx -150 \text{ MeV for } K^+, K^0, \Lambda \) (NN→NAK) and \( \approx -450 \text{ MeV, } \approx -490 \text{ MeV for the } K^- \) (NN→NNK+K−) and the \( \phi \) meson (NN→NNφ). However, the global fit of the function Mult \( \propto \langle A_{\text{part}} \rangle^\alpha \) to all the hadron yields returns a satisfactory value of \( \chi^2/\text{NDF} = 0.59 \), with \( \alpha = 1.45 \pm 0.06 \) [i]. This points to a more involved picture than assumed in the past, as the total amount of produced strangeness increases with the number of participants and might be only redistributed (statistically) to the final hadron species at freeze-out [51]. This implies that the created system is more interrelated than expected in the past.

In the following, we will compare the \( K^0_s \) and \( \Lambda \) data to predictions from three state-of-the-art hadronic trans-

![Fig. 4: Compilation of mid-rapidity yields for central Au+Au (Pb+Pb) collisions as a function of \( \sqrt{s_{\text{NN}}} \) of \( K^0_s \) (red) and \( \Lambda \) (blue) from [39] [41] [43] [49]. Our results are shown by the two left most bullets.]

| \( K^0_s \) | yield \( \times 10^2 \) [1/evt] | \( T_{\text{eff}} \) [MeV] |
|---|---|---|
| 0 - 40% | 1.56 ± 0.03 ± 0.12 | 93 ± 1 ± 4 |
| 0 - 10% | 2.84 ± 0.09 ± 0.27 | 98 ± 1 ± 3 |
| 10 - 20% | 1.58 ± 0.04 ± 0.12 | 98 ± 1 ± 3 |
| 20 - 30% | 1.06 ± 0.03 ± 0.08 | 89 ± 1 ± 1 |
| 30 - 40% | 0.66 ± 0.02 ± 0.06 | 86 ± 1 ± 1 |

| \( \Lambda \) | yield \( \times 10^2 \) [1/evt] | \( T_{\text{eff}} \) [MeV] |
|---|---|---|
| 0 - 40% | 4.72 ± 0.06 ± 0.21 | 98 ± 1 ± 5 |
| 0 - 10% | 8.22 ± 0.11 ± 0.25 | 106 ± 1 ± 2 |
| 10 - 20% | 4.90 ± 0.09 ± 0.21 | 97 ± 1 ± 2 |
| 20 - 30% | 3.17 ± 0.08 ± 0.36 | 90 ± 1 ± 3 |
| 30 - 40% | 1.92 ± 0.08 ± 0.28 | 84 ± 1 ± 4 |

TABLE I: \( K^0_s \) and \( \Lambda \) multiplicities in full phase space and inverse slopes at mid-rapidity \( T_{\text{eff}} \) for a given centrality. The first given error corresponds always to the statistical, the second to the systematic error. See text for details.

![Fig. 5: Multiplicities per mean number of participants Mult/\langle A_{\text{part}} \rangle as a function of \( A_{\text{part}} \). All hadron yields are fitted simultaneously with a function of the form Mult \( \propto \langle A_{\text{part}} \rangle^\alpha \) with the result: \( \alpha = 1.45 \pm 0.06 \).

[i] While in case of the \( K^- \) the similar scaling was explained by a coupling to the \( K^{+0} \) yield via strangeness exchange reactions, e.g. \( \pi^0 + \Lambda \rightarrow K^- + p \) [12], no such process is possible in case of the \( \phi \) meson.

\( \sqrt{s_{\text{NN}}} \) (GeV) | \( dN/dy \) |
|---|---|---|
| 100 | 100 | 100 |
| 200 | 200 | 200 |
| 300 | 300 | 300 |
| 400 | 400 | 400 |

\( \Lambda \) data (\( K^{+0} \), \( \Lambda \), \( \phi \)) | \( \alpha \) |
|---|---|
| 1.45 ± 0.06 |
| 1.69 ± 0.04 |
| 1.35 ± 0.02 |
| 1.51 ± 0.03 |
| 1.30 ± 0.02 |
| 1.42 ± 0.03 |

TABLE II: Values of the parameter \( \alpha \) extracted for \( K^0_s \) and \( \Lambda \) data and various models, as displayed in Fig. 5.
port models, the Isospin Quantum Molecular Dynamics model (IQMDv.c8) [31], the Hadron String Dynamics (HSDv.711n) model [30] and the Ultrarelativistic Quan-
tics model (IQMDv.c8) [31], the Hadron String Dynamics model, the Isospin Quantum Molecular Dynam-
mid-rapidity.

0

FIG. 6: Multiplicities per mean number of participants \(\frac{\text{Mult}}{\langle A_{\text{part}} \rangle}\), as a function of \(\langle A_{\text{part}} \rangle\) for \(K^0_S\) (left) and \(\Lambda\) (right) compared to various transport model calculations (see legends).

FIG. 7: Comparison of the shape of the rapidity distribution of \(K^0_S\) (left) and \(\Lambda\) (right) to various transport model versions. The model curves are normalized to the integral of the data, see text for details. Data are symmetrized around mid-rapidity.

The \(\alpha\) values can be reduced. Due to the associated production of kaons and \(\Lambda\) hyperons, also the \(\Lambda\) yields are affected by the inclusion of a K-N potential. Note that the employed version of UrQMD does not include any potential, while both versions of HSD and IQMD assume the strength of the A-N mean field to be 2/3 of the N-N mean field, motivated by the additive quark model [14]. Next, we compare the shape of the rapidity distributions for 0-10% most central events. For this, we have symmetrized the distributions with respect to mid-rapidity.

In HSD and IQMD, a repulsive K-N potential of 40 MeV at nuclear ground state density \(\rho_0\) is included, which increases linearly with density. If turned on, the \(K^0_S\) curves come much closer to the data and also the \(\alpha\) parameter is reduced. The IQMD predictions are by far the closest to the data with a deviation of the yields of the order of 10% [iii] and an agreement within errors of the extracted values of \(\alpha\). The reduction of the yield and \(\alpha\) values can be understood qualitatively by an effective shift in the production threshold of kaons. As the effect of the density dependence is more pronounced for central events, also the rise with \(\langle A_{\text{part}} \rangle\) is reduced. Due to the associated production of kaons and \(\Lambda\) hyperons, also the \(\Lambda\) yields are affected by the inclusion of a K-N potential.

Note that preliminary data on yields of charged pions show a deviation at the order of 20% to data of the FOPI experi-
ment, which are well described by IQMD [52]. Due to \(\pi\) induced strangeness production channels, this difference is also trans-
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ported to the \(K^0_S\) and \(\Lambda\) yields.
Finally, we study the transverse momentum distribution at mid-rapidity for the most central event class, see Fig. [vii]. Besides the production mechanism [xix] and the radial expansion velocity of the system, the low transverse momentum part is particularly sensitive to the K/Λ-N potentials [xx] [iv]. Once again, in order to compare the shapes, the model curves are normalized to the area of the experimental ones. Clearly, for K$_0^s$ the data favour models which include potentials. However, again UrQMD without any potential shows a completely different behaviour compared to the two other calculations without the potential, undershooting the low $p_t$ part of the spectrum. Hence, production via intermediate resonances seems to (over-) mimic the effect of the potential.

In addition, similar as in case of the rapidity distribution, UrQMD offers the best description of the Λ $p_t$ spectra. In total, we find that none of the model predictions can describe the yield, the $\langle A_{part} \rangle$ scaling and the shape of the rapidity and $p_t$ spectra of K$_0^s$ and Λ simultaneously, see also the $\chi^2$ values normalized to the number of data points listed in Tab. [xxi] for the investigated observables. Furthermore, we observe that effects of a repulsive K-N potential can be to some extend compensated by production via intermediate resonances. Hence, any further conclusions are weakened by the ambiguities of different microscopic effects and the incomplete description of the presented observables within all investigated models. Therefore, it is misleading to draw conclusions on the strength of the potentials based only on a single observable, and it is necessary to compare and describe as many (related) observables as possible within the same model. To enable a comprehensive adjustment of models and new approaches which are under development [54–57] to our data, differential transverse mass versus rapidity plots are shown in the Appendix.

In summary, we present the first data on sub-threshold production of K$_0^s$ mesons and Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV. We observe a universal scaling with $\langle A_{part} \rangle$ for all particles containing strangeness, independent of the corresponding excess energy. This suggests a more interrelated system than assumed in the past in which the total amount of strangeness increases stronger than linear with the number of participants and might be redistributed to the final hadron states only at freeze-out. Previous constraints on the EOS of nuclear matter based on the assumption of energy accumulation in sequential nucleon-nucleon collisions should therefore be revisited.

Our comparison of the yields, the universal scaling and the shapes of rapidity and $p_t$ spectra to three microscopic transport models does not yet lead to a consistent picture. Including a repulsive KN potential the IQMD predictions are by far closest to the data, with a remaining deviation of the yields of the order of 10% and an agreement within errors of the extracted values of $\alpha$. The shape of the kaon rapidity distribution is well described if a repulsive K-N potential is included in HSD and in particular in IQMD. On the other hand, UrQMD reproduces the rapidity distribution without such a potential, probably because of the particle production through intermediate resonances, but fails to reproduce the observed scaling of the yields with centrality. Yet, the shape of the Λ rapidity distributions and the $p_t$ spectra are best described by UrQMD. Due to the observed ambiguities and the imperfect description of the presented observables, it is premature to adjust the strength of the potential to a single observable. Further model refinements and subsequent data-to-model comparisons are necessary before firm constraints can be deduced.

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I. APPENDIX

The observables shown in the text are based on the data presented in Fig. 9 and 10. The data are organized in bins of $m_t - m_0$ vs. $y_{cm}$ for the four centrality classes. The details of the centrality selection are described in [34].