$\Lambda(1520)$ AND ϕ AS POTENTIAL SOURCES OF K^- MESON EMISSION IN HEAVY-ION COLLISIONS AROUND KAON THRESHOLD*

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In the context of search for in-medium modifications of negatively charged kaons emitted from hot and dense nuclear medium, we extracted efficiencies for the measurement of ϕ and $\Lambda(1520)$ from Ag+Ag collisions at beam energy of 1.58 A GeV by the HADES apparatus. Whereas about 18% contribution to K^- spectra results from $\phi \to K^+K^-$ decays, calculations within statistical model suggest the contribution from $\Lambda(1520) \to pK^-$ to be very similar. We found reconstruction efficiencies for ϕ meson and $\Lambda(1520)$ to be about 2% and 3%, respectively. We also estimate that the signal from the latter particle may be too weak to be observed by the HADES Ag + Ag experiment.

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1. Introduction

Investigations of kaon emission in the heavy-ion collisions at beam energies around the threshold for their production in free nucleon–nucleon collisions have often aroused interest due to their sensitivity to in-medium modifications of basic hadron properties, such as mass and decay constant [1]. These effects occurring inside hot and dense nuclear matter are related to the partial restoration of the chiral symmetry and are an intensively studied subject throughout the last decades [2]. From the comparisons of the experimentally obtained kinematic spectra of $K^0_{\rm S}$ to the transport model calculations, the effective masses of these particles were found to be higher than those in vacuum, in accordance with the theoretical predictions [3–5]. Results from the analysis of the directed flow of K^+ emitted from Ni + Ni

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collisions at 1.9 A GeV also suggest a small increase of mass of this particle with density [6]. However, in the case of K^-, the situation appears to be considerably more complex.

A series of analyses of heavy-ion collisions performed by the HADES and FOPI collaborations at beam energies of 1–2 A GeV has shown that a relevant source of negative kaons is the $\phi \to K^+K^-$ decay channel (BR $\approx 49\%$) [7–11] and, possibly, $\Lambda(1520) \to pK^-$ (BR $\approx 22\%$) [12, 13]. The kaons originating from these decays have different kinematic distributions than these emitted directly from the collision zone. In consequence, these contributions can at least partially mimic the effect of in-medium modifications of K^- mesons, and should be quantitatively established. While small samples of ϕ mesons were measured at a few A GeV, the $\Lambda(1520)$ baryons were not yet observed in this energy range.

In March 2019, the HADES Collaboration at GSI, Darmstadt, carried out the Ag + Ag collisions at beam energy of 1.58 GeV per nucleon [17][1]. An exceptionally high statistics of 12×10^9 events combined with the detector's wide acceptance, good granularity and time resolution give a chance for a precise reconstruction of K^- and ϕ meson spectra as well as the $\Lambda(1520)$ signal in this collision system. In this paper, we report the first estimation of efficiency for the measurement of the latter two particles in this experiment. We also give a preliminary evaluation of the possibility of observing a $\Lambda(1520)$ signal.

2. HADES setup and particle identification

The High Acceptance Di-Electron Spectrometer is installed at the SIS18 synchrotron, at GSI, Darmstadt, which provides ion beams with energies of 1–2 GeV per nucleon. A schematic view of this apparatus is shown in Fig. 1. The detector has a hexagonal symmetry with respect to the beam axis (in the following, each segment will be referred to as *sector*), and has a nearly full acceptance in the azimuthal angles. The covered polar angles span 18°–85°. The START detector, positioned in front of the fixed target, provides the start-time signal.

In the following, the detectors relevant for the measurement of hadrons will be described. For each sector, four tracking stations of the Multiwire Drift Chamber (MDC) detector are mounted. A toroidal superconducting magnet is positioned between the second and the third MDC station. A measurement of the deflection angle of a charged particle traversing the magnetic field allows reconstruction of the particle's path (referred to as *track*), as well as its momentum p, and the charge polarity. Behind the MDC, two

[1] A somewhat higher number shown in the reference is due to additional collisions at a different beam energy, measured at the end of the experiment.

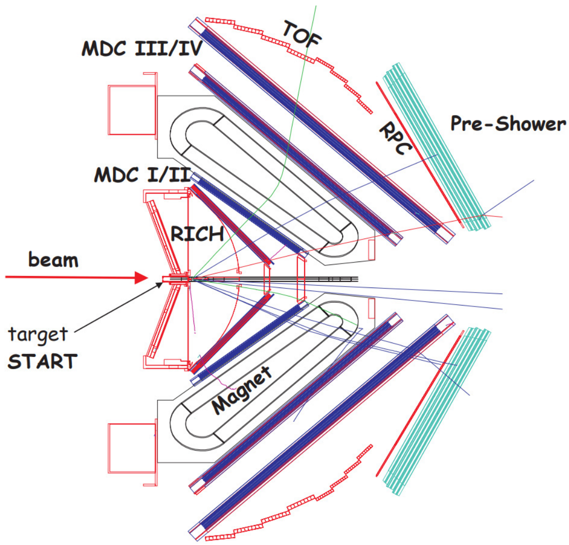

Fig. 1. Schematic expanded view of the HADES setup [18].

Time-of-Flight detectors are installed: the Resistive Plate Chamber (RPC) covers the polar angle range of 18°–45°, whereas the Time-of-Flight (ToF) wall spans 44°–85°. A combination of the particle's momentum with the ToF (RPC) — START time difference allows identification of particles using the momentum-velocity plot, benefiting from the relativistic dependency $p = \gamma m v$, where m is the mass, v — velocity, and $\gamma = \sqrt{1-(v/c)^2}$ is the Lorentz factor. More details on the HADES geometry and performance can be found in [19].

3. Efficiency of a ϕ and $\Lambda(1520)$ measurement in HADES

In order to obtain the realistic efficiency for the measurement of $\phi \to K^+K^-$ and $\Lambda(1520) \to pK^-$ channels, the events corresponding to these decays were first generated within the PLUTO package [14]. The parent particles were produced according to the Boltzmann distribution with three possible temperatures: $T \in \{70, 100, 130\}$ MeV. In order to get a realistic background description, each decay was embedded in an event of an Ag + Ag collision at 1.58 A GeV, simulated using the UrQMD [15] transport model, with the range of impact parameters $b \in [0, 8]$ fm. Such events were processed within the Geant3 framework [16], where the HADES apparatus was implemented together with the hit digitization routines. In order to reconstruct the tracks and match them with the hits in the Time-of-Flight detectors, the events were further analysed by the same off-line routines that were used for the experimental data.

Candidates for the ϕ and $\Lambda(1520)$ decay products were identified as tracks characterized with $m \in [440, 540]$ MeV$/c^2$ (charged kaons) and $m \in [700, 1150]$ MeV$/c^2$ (protons). In addition, for a better signal-to-background ratio, only kaon candidates with $p < 700$ MeV$/c$, and proton candidates with $p < 1500$ MeV$/c$ were accepted. The signals were searched for in the invariant-mass distributions of their respective decay channels, as shown in Fig. 2. Whereas for the K^+K^- pairs the background was found to be very small, for the pK^- pairs, the large number of protons generated a very abundant background spectrum.

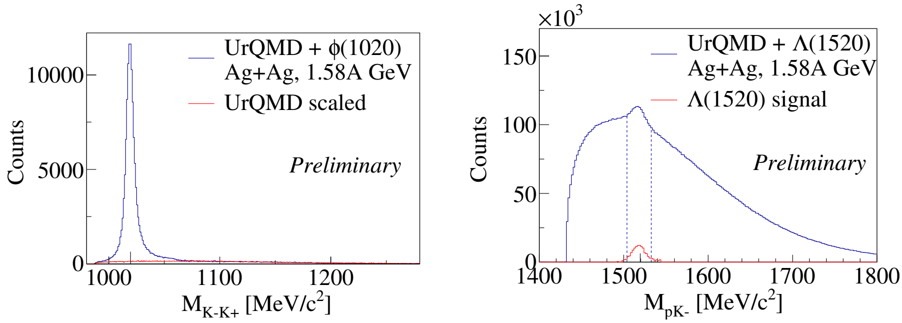

Fig. 2. (Color online) Invariant-mass spectra of K^+K^- (left) and pK^- (right) pairs for events where ϕ (left) or $\Lambda(1520)$ (right) particles were embedded in the UrQMD events of Ag + Ag collisions at 1.58 A GeV. The lower/red curve on the left plot marks the estimated background. On the right plot, the lower/red curve indicates the $\Lambda(1520)$ signal obtained after subtraction of the estimated background, whereas dotted lines denote the $\pm 2\sigma$ range around the centroid.

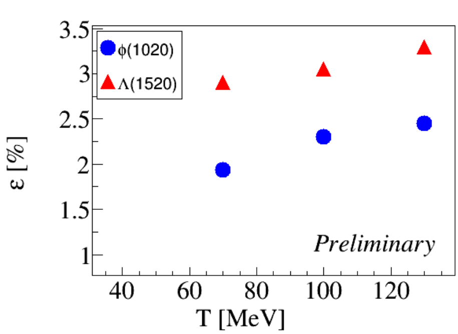

Fig. 3. (Color online) Preliminary efficiency values for the measurement in HADES of particles: ϕ (blue dots) and $\Lambda(1520)$ (red triangles) emitted from Ag + Ag at 1.58 A GeV as a function of their temperatures.

An extraction of peaks corresponding to ϕ and $\Lambda(1520)$ was done by suppressing background from uncorrelated pairs. For this purpose, the background spectrum was generated from UrQMD events processed without the particles in question. The signals were integrated within a $\pm 2\sigma$ window around peak centroids and divided by the input multiplicity of respective particles. The preliminary efficiencies obtained in this way for the three considered temperatures are presented in Fig. 3.

The efficiencies for ϕ are found to be clearly lower than those for $\Lambda(1520)$. The main reason is the presence of two (ϕ) *versus* one charged kaon ($\Lambda(1520)$) in the decay channel. A considerable fraction of these particles, for whose $c\tau = 3.7$ m, decay before reaching any ofthe HADES Time-of-Flight detectors.

4. Can $\Lambda(1520)$ be observed in Ag + Ag collisions?

In March 2019, the HADES Collaboration collected about 12 billion events of Ag + Ag collisions at 1.58 A GeV [17]. The Geant-based simulation described in Sect. 3 allows a first estimate of the possibility of observing $\Lambda(1520)$ in this experiment.

A key ingredient in our reasoning is the yield estimate for this particle, based on the statistical hadronization model calculations for Au + Au collisions at 1.23 A GeV (*cf.* Sect. 4 of [12]). Using the THERMUS code [20], we found that yield to be $P[\Lambda(1520)] = 2.9 \times 10^{-4}$. Only a fraction of 22.5% decays in the pK^- channel [21].

In the absence of known yields for Ag + Ag collisions at 1.58 A GeV, we take this yield as a rough estimate of multiplicity. Moreover, due to lack of knowledge on the inverse slope of $\Lambda(1520)$, we consider the case of $T = 100$ MeV as an estimate of the real conditions. For this case, we find the $\Lambda(1520)$ peak to have the significance of 96 within the range of $\pm 2\sigma$ around the centroid. We then scale the signal from the assumed 1 $\Lambda(1520)$ per UrQMD event down to the $P[\Lambda(1520)] \times \mathrm{BR}$, and renormalize the results by an artificial increase of statistics from 5×10^6 to 1.2×10^{10} events. After these operations, we find that the significance should be 0.3. Within this estimation, we find that the $\Lambda(1520)$ peak should not be observed in the Ag + Ag experiment. It should be noted, however, that there are several unknown factors in this procedure, in particular (1) the fact that the yield for Au + Au is not measured, and (2) assignment of this yield to the case of Ag + Ag.

5. Summary

In this paper, we presented the efficiency calculations for a measurement in the HADES detector of ϕ and $\Lambda(1520)$ emitted from the collisions of Ag + Ag at the beam energy of 1.58 A GeV. For the three considered temperatures of the Boltzmann-like source of these particles, the efficiency for ϕ was found to be in the range of $[1.9, 2.5]\%$ and for $\Lambda(1520)$ — in the range of $[2.9, 3.3]\%$.

In addition, we provide a first estimate of the possibility of observing $\Lambda(1520)$ in the data from Ag + Ag collisions measured by HADES. An emission of this particle has not been observed yet at $\sqrt{s_{NN}}$ below 17 A GeV. Therefore, to estimate its yield for the case analysed in this paper, we used the result of the THERMUS statistical model code for Au+Au at 1.23 A GeV as a rough estimate of the production yield for the Ag+Ag case. After proper weighting of signal as well as background from uncorrelated pK^- pairs, we found that the significance for $\Lambda(1520)$ should be around 0.3, which suggests that this particle should not be observed, under the assumptions applied.

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