WHAT CAN WE LEARN FROM THE $\phi(1020)$ MESON PRODUCTION AT SIS ENERGIES?*

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Kaon yields measured in nucleus–nucleus collisions can be affected by the decays of $\phi(1020)$ mesons into hadronic channel. In this contribution we report on the study of ϕ meson production in Al+Al collisions at $1.9A$ GeV. The measurement was done at SIS18 (GSI Darmstadt) with the FOPI Spectrometer. The fraction of the K^- yield originating from ϕ decay was found to be $(10 \pm 5)\%$ in rough agreement with recent HADES measurements for Ar+KCl system.

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1. Motivation

Strange particles are very sensitive probes of hot and dense nuclear matter formed in the relativistic nucleus–nucleus collisions. During such a collision at energies in the range 1–$2A$ GeV (SIS energy range) the density of nuclear matter in the central region of the collision (so called *fireball*) increases up to 2–3 normal densities. Temperature of the fireball reaches 100 MeV. Such conditions last for a very short period of time (10–20 fm/c) in which new particles are produced. The production probabilities and phase-space distributions of different particle species registered in heavy-ion experiments depend on the conditions reached in the "fireball". Thus, they can reflect thermodynamical properties of the hot and dense nuclear matter, as well as theoretically anticipated in-medium modifications of hadrons' properties and interactions between them.

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1.1. Properties of the fireball

Conditions in the fireball during the chemical and kinematical freeze-out can be investigated by studying particle production. Particle yields ratios can be compared to the statistical model to obtain "chemical temperature" (T_{chem}) and baryochemical potential (μ_b), parameters which describe the chemical freeze-out conditions. Comparison of the particle ratios to the thermal model predictions can verify, if the colliding system may be treated as equilibrated under the thermodynamic assumptions used with this model. In this paper ϕ/K^* ratio is presented. Also, the Boltzmann "kinetic" temperature was extracted from the measured energy spectrum of ϕ mesons.

The ϕ meson production at SIS energies was recently reported. FOPI Collaboration has measured ϕ yield in Ni+Ni collisions at $1.93A$ GeV in two separate experiments [1,2]. The number of ϕ mesons found in the experimental data sample was, respectively, 23 and 100 and the following total ϕ yields in full 4π geometry were obtained: $(1.2\pm0.4\pm0.6)\times10^{-3}$ [1] and $(6\pm1\pm2)\times 10^{-4}$ [2] per collision. HADES Collaboration measured ϕ meson production on KCl target irradiated with $1{,}756A$ GeV Ar beam. They found $168\pm18\phi$ mesons in their sample and obtained the yield $P(\phi)=(2.6\pm0.7\pm0.1^{+0.0}_{-0.3})$ $\times10^{-4}$ per collision [3].

1.2. In-medium modifications of hadrons

It is predicted that in a dense nuclear matter the kaon–nucleon (KN) interaction is modified with respect to the one in vacuum [4]. K^+ mesons are expected to feel an repulsive potential, whereas K^- should be attracted. As a result of such KN interactions the mass and the production threshold energy for kaons should increase, whereas for antikaons corresponding values should decrease substantially [5]. The in-medium modifications of kaons' properties have been already reported by several experiments focused on strangeness production at sub-threshold energies (*e.g.* FOPI, KaoS in GSI) [6, 7]. Conclusions were based on the comparison to the results of theoretical transport models which seldom consider a potentially important kaon-production channel, which involves the production and subsequent decays of ϕ mesons [8]. Almost half of the ϕ mesons (49.2 ± 0.6 % [9]) decay into charged kaon pairs $\phi\to K^+K^-$. Essential for the in-medium modifications studies is to investigate the ϕ meson yield which can substantially affect the measured K^- meson production probability and phase-space population. It has been reported that even as much as 20% of K^- mesons produced in Ni+Ni collisions at $1.9A$ GeV beam energy can originate from ϕ decays [1]. According to the HADES measurements in Ar+KCl system at $1.756A$ GeV (18 ± 7) % K^- originate from the ϕ decays [3].

2. FOPI detector

FOPI is a modular detector for the fixed-target experiments at the SIS synchrotron in GSI-Darmstadt. It consists of 5 subdetectors: CDC (Central Drift Chamber), MMRPC(Multi-strip Multi-gap Resistive Plate Chamber ToF detector), Barrel (plastic scintillator ToF detector), Helitron (forward drift chamber) and Forward Plastic Wall (see Fig. 1). Drift chambers, plastic Barrel and MMRPC detectors are located within the magnetic field of 0.6 T. This set-up is capable of measuring directly charged products of the reaction in the almost complete 4π geometry. The mass of the particle is calculated from magnetic rigidity and energy loss measurements in drift chambers. Plastic detectors, as well as MMRPCs, give an addition information about the time of flight. Matching hits in the ToF detectors with tracks reconstructed in drift chambers enhances mass resolution capabilities. Neutral particles can be identified in the FOPI spectrometer only by reconstructing invariant masses of charged products of their decay.

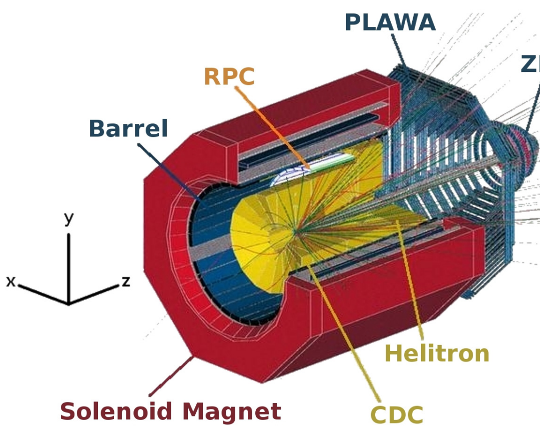


Fig. 1. FOPI experimental setup. Barrel, PlaWa (Plastic Wall), ZDC (Zero Degree Counter) are position-sensitive plastic scintillator detectors used for time-of-flight (ToF) and energy loss (ΔE) measurements. RPC (Multi-strip Multi-gap Resistive Plate Chamber) is high-resolution, position-sensitive detector for ToF and ΔE measurements. CDC (Central Drift Chamber) and Helitron are multi-wire drift chambers enabling tracking and $\Delta E/\Delta x$ measurements.

3. Results

In the experiment reported in this work, the aluminum target of $0.567\ \mathrm{g/cm^2}$ thickness was used. It was irradiated by the beam of aluminum ions of roughly $8 \times 10^5\ \mathrm{s^{-1}}$ intensity. The kinetic energy (E_{kin}) of the beam was 1.91 GeV per nucleon ($\sqrt{S_{NN}} = 2.65$ GeV). The number of collected central Al+Al events was 3×10^8. The events are selected by their centrality which is determined by the multiplicity of charged particles in CDC and Forward Plastic Wall. The results presented in the following work are based on the most central events corresponding to 20% of the total geometrical cross-section.

3.1. ϕ(1020) yield and its kinetic energy distribution

The threshold energy for the ϕ meson production ($m_\phi = (1019.455 \pm 0.020)$ MeV/c^2 [9]) in NN collision equals to 2.6 GeV. This means that ϕ mesons registered in the Al+Al experiment at 1.9A GeV beam kinetic energy could be produced entirely due to the collective effects and/or Fermi motion of nucleons inside nuclei. ϕ is a neutral, vector meson which contains the pair of strange quark–antiquark ($s\bar{s}$). ϕ mesons produced in heavy-ion collisions decay mostly outside the fireball, because of relatively long lifetime ($c\tau \approx 45$ fm). Hence, $K^\pm$ mesons that follow from such decays can reach detectors without changing their momenta due to the final-state interactions, and ϕ mesons can be identified experimentally by reconstructing invariant masses of the registered K^+K^- pairs. The invariant mass spectrum of K^+K^- pairs registered in the Barrel+CDC subsystem is shown in the upper panel of Fig. 2.

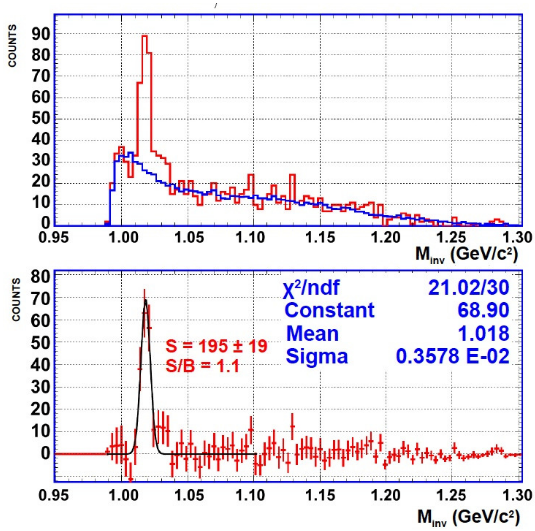


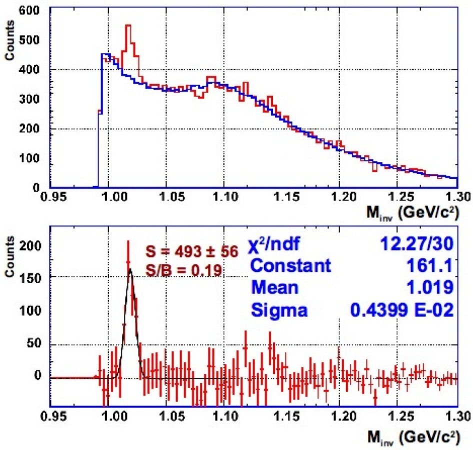
Fig. 2. Invariant mass spectrum of K^+K^- pairs with the shape of the combinatory background (upper panel). Lower plot shows invariant mass spectrum after background subtraction, with Gaussian fit to the peak corresponding to ϕ meson decays.

The background was reconstructed using event-mixing method [10]. After background subtraction, clear peak, centered around the nominal mass of ϕ meson, consisting of about 200 counts is seen. In order to get the ϕ meson production probability, the efficiency of the detector was estimated using GEANT package. Total yield was obtained under the assumption of isotropic, thermal source according to the Siemens–Rasmussen formula [11] which describes an expanding system with a temperature T and a radial expansion velocity β.

The generated ϕ source had a velocity of radial flow $\beta = 0$ and temperature within the range from 70 to 130 MeV. Different temperatures of the source were taken into account to estimate the systematic uncertainties. The background accompanying the ϕ mesons in each event was composed of Al+Al events generated with the UrQMD code. The resulting ϕ yield in Al+Al collisions at $1.91A\,\mathrm{GeV}$ beam energy was found to be $P_\phi = (2.2 \pm 0.5) \times 10^{-4}$ per collision, in agreement with the HADES results obtained within the similar system of colliding nuclei [3]. The discrepancies between result obtained in the case of Al+Al collisions and the Ni+Ni experiment may be caused by the system-size dependence of ϕ meson production. Studies concerning mean number of participants in the central zone of the collisions in each of these experiments should verify this hypothesis. Data from the new FOPI experiments will be available in the future.

To reconstruct kinetic energy spectrum of ϕ mesons, it was essential to enlarge the amount of reconstructed ϕ mesons. In the CDC+Barrel subsystem the phase-space was limited by the angular coverage of plastic Barrel: $27^\circ < \Theta_{\mathrm{lab}} < 57^\circ$, where Θ_{lab} is a polar angle in the laboratory frame. To enlarge the phase-space of reconstructed ϕ mesons, kaons identified only in the Central Drift Chamber (CDC) were taken into account. The CDC covers the $23^\circ < \Theta_{\mathrm{lab}} < 133^\circ$ region in the laboratory polar angle. The invariant mass spectrum of K^+K^- pairs found in the CDC only (Fig. 3) suffers a higher background compared to that based on the kaons identified using Barrel and CDC detectors. However, the signal contains almost 500 counts, factor 2.5 more compared to the yield of ϕ mesons identified in the CDC+Barrel subsystem. With such a statistics the kinetic energy spectrum of ϕ mesons could be constructed — Fig. 3. On the right picture of Fig. 3 the kinetic energy distribution in the CM frame of produced ϕs is shown. Points are corrected with the detector's efficiency. Black, thick line represents the Boltzmann function (Eq. 1) fitted to the experimental points

$$f(E) \propto p\,E\,\exp\left(\frac{-E}{T_{\mathrm{B}}}\right) . \qquad (1)$$



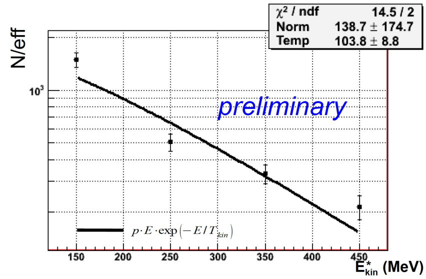


Fig. 3. Left panel: invariant mass spectrum of K^+K^- pairs found in the CDC only. Lower plot shows the spectrum after the background subtraction. Right panel: Kinetic energy spectrum of reconstructed ϕ mesons. Experimental points are corrected for the detector efficiency. Solid line represents the Boltzmann function fit.

Effective temperature parameter was obtained to be equal $T_{\rm B} = (104 \pm 9)$ MeV with the statistical error only. The systematical error still requires detailed evaluation.

3.2. Particle yield ratios — ϕ/K^*, ϕ/K^-

From the data obtained in the described experiment, 2 new particle yield ratios were calculated. The ϕ/K^* ratio was obtained using the result on K^* production in Al+Al collisions [12, 13]. K^* yield was calculated using the same method as for the ϕ production probability. Final result takes into account the full 4π geometry of the detector. Simulated K^* came from the thermal source with the same temperature. It turned out that the ϕ/K^* ratio is equal to 0.18 ± 0.02. This ratio is now analyzed within the thermal model (see [14] in this volume).

ϕ/K^- ratio was calculated using already known particle yield ratios:

- $K^*/K^0 = 0.032 \pm 0.012\,,$ [13]
- $K^-/K^+ = 0.031 \pm 0.006\,.$ [15]

Hence, combining known ratios we can calculate the ϕ/K^- as follows:

$$\frac{\phi}{K^-} = \frac{\phi}{K^*}\frac{K^*}{K^0}\frac{K^+}{K^-} = 0.2 \pm 0.1\,, \tag{2}$$

assuming the same production rate of K^+ and K^0 mesons from the isospin doublet. ϕ/K^- ratio measured with the HADES spectrometer for Ar+KCl at $1.756A$ GeV was found to be 0.37 ± 0.13. This result is twice larger than one obtained in this work, however in agreement because of large uncertainties of both measurements. In the case of presented work ϕ/K^- ratio was calculated using the results obtained within the other experiments. To verify the ϕ/K^- ratio future analysis should aim at estimation of total K^- meson yield in the Al+Al experiment within the FOPI geometry. In this way, the effect of the production and subsequent decays of ϕ meson on the K^- meson production in heavy-ion collisions will be studied in details and the final result of ϕ/K^- ratio will be presented.

Taking into account the branching ratio of the $\phi \to K^+K^-$ decay channel, it turns out that $(10 \pm 5)\%$ of K^- mesons originate from the ϕ meson decay. This implies that ϕ production contributes significantly to the K^- rate.

4. Conclusions and outlook

In summary, we have presented new results on $\phi(1020)$ meson production in Al+Al collisions at $1.9A$ GeV. Obtained ϕ meson yield is in a good agreement with the results reported recently by the HADES Collaboration for a similar system. Particle yield ratios presented in this work can be used as an input to the thermal models. Finally, ϕ/K^- ratio shows the significant contribution to the K^- production rate in nuclear collisions.

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