KAON, ANTIKAON AND $\phi(1020)$ PRODUCTION IN Al+Al COLLISIONS AT 1.9 A GeV*

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In this paper the production of K^+, K^- and ϕ mesons in Al+Al collisions at incident beam energy of 1.9A GeV is studied. The experiment was performed in GSI/Darmstadt using the FOPI spectrometer. The K^-/K^+ yields ratio was extracted in a substantial part of the phase-space. The yields ratio was found to be in a good agreement with previous experimental results that served as a proof for in-medium modifications of kaons' properties. In order to quantify the contribution of ϕ mesons decays to the observed K^- mesons yield, the ϕ meson production probability was estimated. The preliminary result differs by almost two orders of magnitude from the earlier estimate available for heavier (Ni+Ni) system at similar beam energy, in which the number of K^- mesons that could stem from ϕ mesons decays was found to be as high as 20%.

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1. Motivation

In central nucleus–nucleus collisions at incident beam energies of 1–2 A GeV, nuclear matter can be compressed to densities that are 2–3 times larger than the normal nuclear matter density ($\rho_0 \approx 0.17$ fm^{-3}). Such conditions exist in the central zone of collisions, so called "fireball", which lasts for a very short period of time (10–20 fm/c). The temperature of the nuclear matter inside the "fireball", where new particles are produced, reaches about 100 MeV. The production probabilities and phase-space distributions of different particle species registered in heavy-ion experiments depend on the

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conditions reached in the "fireball". Thus, they can reflect thermodynamical properties (such as the equation of state) of the hot and dense nuclear matter, as well as theoretically anticipated in-medium modifications of hadrons' properties and interactions between them.

1.1. Strangeness production in A–A collisions

At beam energies below $2\,A\,\mathrm{GeV}$, kaons are mainly produced inside the "fireball". Moreover, because of a high threshold-energy for a production in a single NN collision ($E_{\mathrm{th}} \approx 1.6\,\mathrm{GeV}$ for K^+, $E_{\mathrm{th}} \approx 2.5\,\mathrm{GeV}$ for K^-), a large number of kaons is produced in multi-step processes. For example, ΔN or πN reactions [3] contribute substantially to the overall K^+ meson yield. On the other hand, the strangeness exchange reaction $K^- N \rightleftharpoons \pi Y$ (where Y is a $\mathit{\Lambda}$ or Σ hyperon) is important in the case of the $K-$ production [4]. Because of the small cross section of the subsequent elastic scattering and due to the strangeness-conservation rule, K^+ mesons have a chance to leave the interaction zone relatively undisturbed in the later phases of the reaction.

It is also predicted that in a dense nuclear medium the K–N interaction is modified with respect to the one in vacuum. Due to the surrounding medium, kaons are believed to feel an additional repulsion, whereas the interaction is thought to become more attractive for antikaons. Because of that, the mass and the threshold energy for production of K^+ mesons should effectively increase, whereas the effective mass of the antikaons and the corresponding threshold energy should decrease substantially [2].

Already a few experiments that focused on the production of strangeness in heavy-ion collisions at sub-threshold energies (*eg.* KaoS, FOPI in GSI/Darmstadt) reported evidence for the in-medium modifications of kaons' properties predicted by various theoretical models [3, 5]. However, usually conclusions have been drawn without considering a potentially quite important kaon-production channel, which involves the production and subsequent decays of ϕ mesons. According to the PDG report, the ϕ mesons decay with a 49.2% probability and a mean-lifetime of $c\tau = 46.3$ fm into charged-kaons pairs: $\phi \to K^+K^-$. Depending on the initial number of produced ϕ mesons, this 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 $1.9\,A\,\mathrm{GeV}$ beam energy can originate from ϕ decays [6].

In this paper the results of the analysis of the K^+, K^- and ϕ mesons production in Al+Al collisions at $1.9\,A\,\mathrm{GeV}$ incident beam energy are presented. The K^-/K^+ yields ratio as a function of rapidity and transverse momentum is extracted and the ϕ mesons production probability is estimated and compared to previous results obtained in the case of Ni+Ni collisions at $1.93\,A\,\mathrm{GeV}$ beam energy.

2. Experimental setup — FOPI detector

FOPI is a modular detector for fixed-target experiments at the SIS accelerator in GSI-Darmstadt. It is capable of measuring directly charged reaction-products in the almost complete 4π geometry. Neutral particles can be identified in the FOPI spectrometer only by reconstructing invariant masses of their charged decay-products. The FOPI spectrometer consists of 4 subdetectors: CDC (Central Drift Chamber), Barrel (plastic scintillator ToF detector), Helitron (forward drift chamber) and Forward Plastic Wall (see Fig. 1).

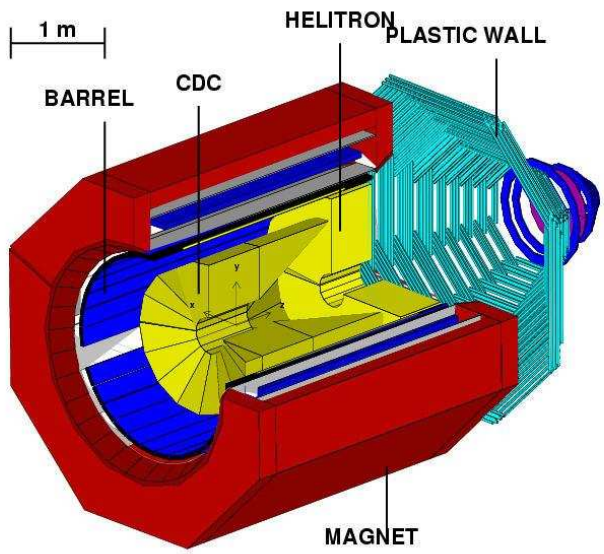

Fig. 1. FOPI experimental setup.

In the analysis presented in this paper, ϕ mesons were reconstructed only from charged-kaon pairs registered in the CDC and the Barrel. In normal conditions, the CDC covers the $23° < \Theta_{\rm lab} < 133°$ region in the laboratory polar angle and has a complete, 2π, acceptance in azimuthal angle. The laboratory polar angle coverage of the Barrel is restricted to $27° < \Theta_{\rm lab} < 57°$. In the CDC, charged particles are identified by measuring their magnetic rigidity, $p/z = B/\rho$, (where p is a momentum of the particle and z is its charge) and their specific energy loss, dE/dx. In addition, tracks registered in the CDC are matched to hits in the scintillator strips of the surrounding Barrel, and the particle-identification capability is enhanced by adding the information about the time-of-flight of a particle, ToF.

3. Results

In the experiment reported in this work, the aluminium target of about $0.702\,\mathrm{g/cm^2}$ thickness was used. It was irradiated by the beam of aluminium ions of roughly $5 \times 10^4\,\mathrm{s^{-1}}$ intensity. The kinetic energy (E_{kin}) of the beam was 1.91 GeV per nucleon ($E_{\mathrm{cm}} = 2.65$ GeV per nucleon). The number of collected central Al+Al events was 3×10^8.

3.1. Kaons in Al+Al collisions

In the analysis presented in this work, the geometric acceptance was additionally limited by selection imposed on momenta of kaons: $p < 0.35\,\mathrm{GeV}/c$ and the polar angle range $135° < \Theta_{\mathrm{cm}} < 155°$. Other selection criteria were imposed on the quality of particle-tracks in order to reduce the background of misidentified particles and to allow for most effective selection of kaons. However, the effects of the selection criteria are supposed to be small and to cancel out to a large extent when particle-yields are studied in terms of their ratios.

In Fig. 2, the K^-/K^+ yields ratio is presented as a function of the kinetic energy in the center of mass frame ($E_{\mathrm{kin}}^{\mathrm{CM}}$) and as a function of the normalized rapidity ($y^{(0)} = y/y^{\mathrm{CM}} - 1$).

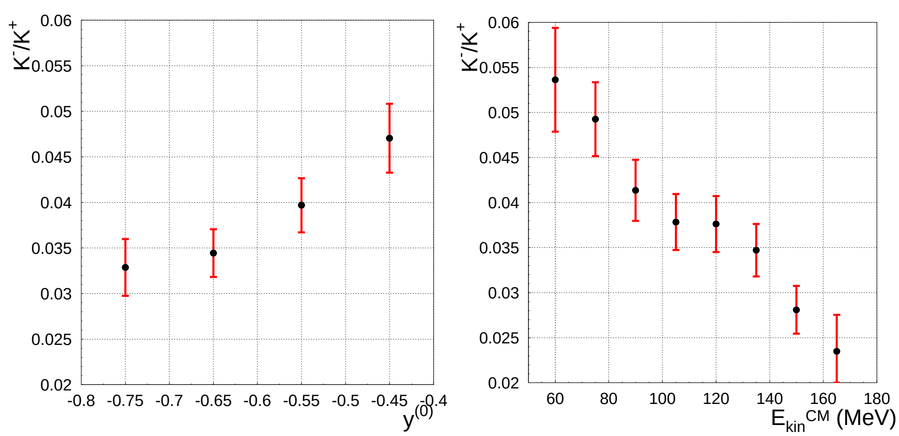

Fig. 2. K^-/K^+ ratio as a function of rapidity (left panel) and kinetic energy in the CMS reference frame (right panel).

The results are qualitatively in a good agreement with those obtained in the case of the Ni+Ni experiment at $1.9\,A$ GeV beam kinetic energy [5]. The extracted yields-ratio increases with the rapidity and decreases with the kinetic energy in the CM frame. In [5], a similar observation was explained as a result of an additional attraction of the K^-N potential and an additional repulsion felt by K^+ mesons in the dense medium. Detailed comparison to the results of various transport-model calculations, lead to the strength of the K^-N attraction of about -70 MeV and the repulsion of the K^+N potential of about $+30$ MeV. Although qualitatively similar, the yields ratio obtained in the Al+Al experiment obviously differs from that of the Ni+Ni one in terms of the absolute numbers. This can be attributed to the fact that the Al+Al system is 2 times lighter than the Ni+Ni one, and that the geometrical acceptance of the setup was shifted to more backwards angles in the Ni+Ni experiment. Quantitative comparison of the two experiments and of the resulting conclusions will be possible when appropriate model calculations for the Al+Al system will be available.

Nevertheless, one has to keep in mind that the theoretical calculations, to which the experimental results are compared and which provide the ground for drawing the conclusions, for example, about the strength of the kaon–nucleon potentials, so far, do not take into account that decays of ϕ mesons could contribute substantially to the charged kaon production. This assumption does not necessarily hold in all cases and should certainly be verified experimentally. The next section of this paper addresses the question of the ϕ meson production in the Al+Al experiment and its possible influence on the measured K^- meson yield.

3.2. ϕ mesons production

The threshold energy for the ϕ meson production in a NN collision is $E_{\mathrm{th}} \approx 2.6$ GeV. This means that ϕ mesons registered in the Al+Al experiment at 1.9 A GeV beam kinetic energy could be produced entirely due to collective effects and/or Fermi motion of nucleons inside nuclei.

Because of a relatively long life-time ($c\tau \approx 45$ fm) ϕ mesons produced in heavy-ion collisions decay mostly outside the fireball. Hence, $K^\pm$ mesons that follow from such decays can reach detectors without changing their momenta due to final-state interactions, and ϕ mesons can be identified experimentally by reconstructing invariant masses of the registered K^+K^- pairs. In the upper panel of Fig. 3 the spectrum of invariant masses of kaon-antikaon pairs registered in all 3×10^8 collected Al+Al central events is shown. A clear peak, consisting of about 200 counts, centred around the nominal mass of the ϕ meson (1.020 GeV/c^2) can be seen. A relatively small background can be quite well reproduced by the event-mixing technique, in which one calculates the invariant masses of K^- and K^+ mesons taken from different events. In order to enlarge the statistics of the mixed-event method, each K^- candidate was mixed with 20 K^+ mesons. In addition, in order to overcome the detector bias, such as, for example, tracking deficiencies, kaon-antikaon pairs were taken from events in which similar number of particles were detected in the CDC. The lower panel of Fig. 3 shows the invariant mass spectrum of K^-K^+ pairs after subtraction of the background normalized in the region which is depicted in the upper panel by the shaded area.

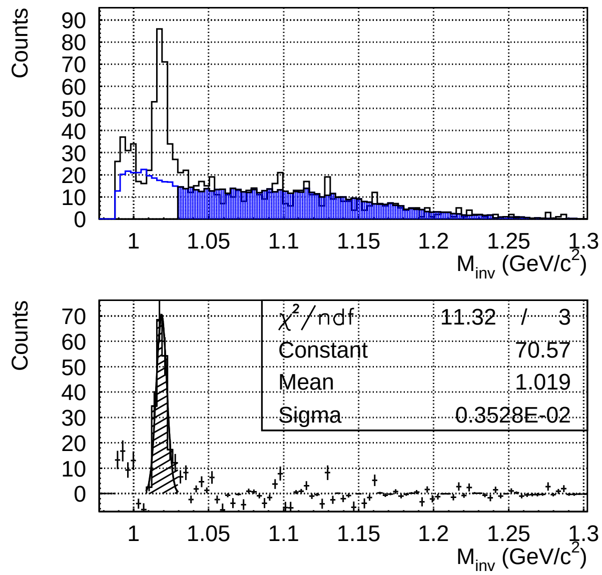

Fig. 3. Invariant mass spectrum of K^+K^- pairs. Upper plot shows $M_{\rm inv}$ spectrum with marked, reconstructed background. Lower plot shows $M_{\rm inv}$ after background subtraction, with Gaussian fit to the peak corresponding to ϕ meson decays.

After the background subtraction, Gaussian function is fitted in the range $M_{\rm inv} = 1.01$–$1.28\,{\rm GeV}/c^2$. The fit gives the mean mass of $M_\phi = 1.0188 \pm 0.0004\,{\rm GeV}/c^2$ and the number of reconstructed ϕ mesons $N_\phi = 189 \pm 17 \pm 5$. In order to estimate the ϕ meson detection efficiency, simulations that include a realistic description of the detector geometry and resolution were performed. The global reconstruction efficiency depends on assumptions about the input distribution of ϕ mesons in the phase-space that is fed into the simulation software. In this work, a so-called Siemens–Rasmussen thermal distribution with temperature 100 MeV and radial $flow$ velocity of 0.3 was used. The background accompanying the ϕ mesons in each event was composed of Al+Al events generated with the IQMD code. In such scenario, the global detection efficiency of ϕ mesons reconstruction turned out to be $(1,90 \pm 0.02)\%$. The resulting production probability of ϕ mesons in Al+Al collisions at $1.9\,A\,{\rm GeV}$ beam energy was estimated to be $P_\phi = (4.9 \pm 1.1) \times 10^{-5}$ in the full solid angle.

4. Conclusions and outlook

The result of the present work can be compared to the ϕ-meson production probability of $3.6 \pm 3.0 \times 10^{-3}$ obtained in [6] in the case of Ni+Ni collisions at 1.9 A GeV beam kinetic energy. The present result is about two orders of magnitude smaller than results from the Ni+Ni experiment. This huge discrepancy can be attributed partially to the difference in the size of the colliding systems, which could easily account for about 4 times smaller ϕ mesons production probability in the two times smaller Al+Al system. One also should take into account that in the case of the Ni+Ni experiment, only about 23 ϕ mesons were reconstructed in about 4.6×10^6 central Ni+Ni collisions, which gives rise to a large statistical uncertainty of that result.

In the next step, the total K^- meson production probability in the Al+Al experiment will be estimated and compared to the ϕ meson yield. The comparison will help to understand the small ϕ-meson production probability measured in the Al+Al system. 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 quantified, and the intriguing effect observed in the Ni+Ni system will be verified.

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