What can we learn from the subthreshold $\phi(1020)$ production?

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Abstract. Strange particles are sensitive probes of hot and dense nuclear matter formed in the relativistic nucleus - nucleus collisions. In our experimental studies performed at SIS18 (GSI Darmstadt) with the FOPI spectrometer, we have measured the $\phi(1020)$ meson production in Al+Al collisions at 2A GeV. The production of $\phi(1020)$ mesons, almost half of them decaying via the $K^+K^-$ channel, obviously affects the rate of kaon production. In order to quantify the contribution of $\phi$ mesons decays to the observed $K^-$ mesons yield, the $\phi$ meson production probability was estimated.

1. Motivation
It is predicted that in nuclear matter the kaon-nucleon ($KN$) interaction is modified with respect to vacuum [1]. $K^+$ mesons are expected to feel a repulsive potential, whereas $K^-$ mesons should be attracted. As a result, the effective mass and the production threshold energy for kaons should increase slightly, while for antikaons corresponding values should decrease [2]. The in-medium modifications of kaon properties have been already reported by several experiments focused on strangeness production at SIS18 energies [3, 4]. Conclusions were based on the comparisons to the results of transport models. Those models, however, seldom consider the kaon production channel that involves the creation and subsequent decay of $\phi(1020)$ mesons [5]. It should be noted, that the $\phi$ meson mass is only $\sim 30$ MeV/$c^2$ larger than the mass of a $K^+K^-$ pair. Investigation of $\phi$ meson production may therefore be essential for the conclusions about in-medium effects on kaons, as $\phi$ decays may substantially affect the measured $K^-$ yield and phase-space population.

$\phi$ meson production continues to be the subject of intensive studies at SIS18 energies. The FOPI Collaboration has measured $\phi$ yield in Ni+Ni collisions at 1.93A GeV in two separate experiments [6, 7]. The number of $\phi$ mesons found in the experimental data samples were respectively 23 and 100, resulting in the following total $\phi$ yields extrapolated to 4$\pi$ geometry: $(12 \pm 4 \pm 6) \times 10^{-4}$ [6] and $(6 \pm 1 \pm 2) \times 10^{-4}$ [7] per collision. The HADES Collaboration measured $\phi$ meson production on KCl target irradiated with a 1.756 A GeV Ar beam. They found 168 $\pm 18 \phi$ mesons in their data sample and obtained a yield $P(\phi) = (2.6 \pm 0.7 \pm 0.1^{+0.0}_{-0.3}) \times 10^{-4}$ per collision [8]. The $\phi/K^-$ ratio has also been estimated in the articles mentioned above. It has been reported that even as much as 20% of the $K^-$ mesons produced in Ni+Ni collisions at...
Figure 1. FOPI experimental setup. Barrel and PlaWa (Plastic Wall) are position-sensitive plastic scintillator detectors used for time-of-flight (ToF) and energy loss (ΔE) measurements. CDC (Central Drift Chamber) and Helitron are multi-wire drift chambers enabling tracking and ΔE/Δx measurements.

1.9 A GeV beam energy can originate from Φ decays [6]. According to the HADES measurements in the Ar+KCl system at 1.756 A GeV, (18 ± 7)% K− originate from Φ decays [8].

In this work we studied Φ meson production in $^{27}$Al+$^{27}$Al collisions at 1.9 A GeV beam energy. The measurement was done at SIS18 (GSI Darmstadt) with the FOPI spectrometer.

2. FOPI spectrometer
FOPI is a modular detector dedicated for the fixed-target experiments at the SIS18 synchrotron in GSI-Darmstadt. It consists of 4 subdetectors: CDC, Barrel, Helitron and Forward Plastic Wall (see figure 1). The drift chambers and the plastic Barrel are located within the magnetic field of 0.6T. This set-up is capable of measuring directly the charged products of the reaction in almost complete 4π geometry. The mass of the particle is calculated from magnetic rigidity and energy loss measurements in drift chambers. Plastic detectors give additional 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 their invariant masses using charged decay products.

3. Results
In the experiment reported in this work, an aluminum target of 0.567 g/cm² thickness was irradiated by a beam of aluminum ions of roughly $8 \times 10^5$ s⁻¹ intensity. The kinetic energy of the beam was 1.91 GeV per nucleon. The number of collected central Al+Al events was $3 \times 10^8$. The events were selected by their centrality which is determined by the multiplicity of charged particles in the CDC and Forward Plastic Wall detectors. 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. \( \phi(1020) \) yield

The \( \phi \) is a neutral, vector meson with a mass of \( m_{\phi} = (1019.455 \pm 0.020) \text{MeV}/c^2 \) [11]. It contains a strange quark-antiquark (\( s \bar{s} \)) pair. The threshold energy for \( \phi \) meson production in an \( NN \) collision equals 2.6 GeV, which means that \( \phi \) mesons created in the Al+Al experiment at 1.9A GeV kinetic beam energy are produced entirely due to the collective effects and/or Fermi motion of nucleons inside nuclei. \( \phi \) mesons produced in nucleus-nucleus collisions decay mostly outside the fireball, because of the relatively long life-time \((c\tau \approx 45 \text{fm})\). Therefore, kaons originating from \( \phi \) decays can reach the detectors without changing their momenta from the final-state interactions, so \( \phi \) mesons can be identified experimentally by reconstructing the invariant masses of the registered \( K^+K^- \) pairs \((48.9\pm0.5\% \text{ of all decays} [11])\). The invariant mass spectrum of \( K^+K^- \) pairs detected in the Barrel+CDC subsystem is shown in the upper panel of figure 2.

![Figure 2](image_url)

**Figure 2.** The invariant mass spectrum of \( K^+K^- \) pairs with the combinatorial background superimposed (upper panel). The lower plot shows invariant mass spectrum after background subtraction, with a gaussian fit to the peak corresponding to \( \phi \) meson decays.

A relatively small background can be reconstructed using the event-mixing method [12]. After background subtraction, clear peak, centered around the nominal mass of \( \phi \) meson, consists of 195\pm19 counts. In order to estimate the \( \phi \) meson detection efficiency, simulations that include a realistic description of the detector geometry and resolutions were performed using the GEANT package. The global reconstruction efficiency was obtained assuming an isotropic, thermal source. The generated \( \phi \) source had a temperature within the range from 70 to 130 MeV. Different temperatures of the source were used to estimate the systematic uncertainties. The background accompanying the \( \phi \) mesons in each event was composed of Al+Al events generated with the UrQMD code [9, 10]. The resulting \( \phi \) yield in Al+Al collisions at 1.91A GeV beam energy was found to be \( P_{\phi} = (2.2 \pm 0.5) \times 10^{-4} \text{ per collision} \) [13], in agreement with the HADES results obtained with a similar system of colliding nuclei, but at 8\% lower beam energy [8].

3.2. \( \phi/K^- \) ratio

In the mass spectrum of negatively charged particles, about 6000 \( K^- \) mesons were found. Preliminary analysis of the angular distribution and kinetic energy spectra of the negative kaons, with proper efficiency estimation, allowed determination of the \( K^- \) yield to be equal \( P_{K^-} = (8.1 \pm 1.7 \pm 0.2) \times 10^{-4} \) per collision, with the statistical and systematic errors respectively. Dividing the \( \phi \) and \( K^- \) production yields, one obtains a \( \phi/K^- \) ratio equal to
**Figure 3.** *Left panel:* mass spectrum of negatively charged particles, with momentum $p < 0.38 \text{ GeV/c}$ detected in the spectrometer. The $K^-$ signal, around the mass value of $0.5 \text{ GeV/c}^2$, is visible on the tail of the strong pion signal, which is described with the exponential function (red line). *Right panel:* the kaon signal after background subtraction. The red curve represents a gaussian fit. About 6000 $K^-$ mesons were found in this sample.

0.27 ± 0.10. From the known branching ratio of the $\phi \rightarrow K^+K^-$ decay channel, it turns out that $(14 \pm 5)\%$ of the $K^-$ mesons originate from the $\phi$ meson decays. This implies that $\phi$ production contributes significantly to the $K^-$ yield and should be taken into account while drawing conclusions about kaon in-medium production.

4. Conclusions and outlook
In summary, we have presented new results on $\phi(1020)$ meson production in Al+Al collisions at 1.9A GeV. The resulting $\phi$ yield in Al+Al collisions at 1.91A GeV beam energy was found to be $P_\phi = (2.2 \pm 0.5) \times 10^{-4}$ per collision [13], in agreement with the HADES results obtained within a similar system of colliding nuclei [8]. The discrepancies between the results obtained in the Al+Al and the Ni+Ni experiments [6, 7] may be caused by the system-size dependence of $\phi$ meson production. Studies concerning the 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 on this subject will be available in the future. Finally, the preliminary $\phi/K^-$ ratio shows a significant contribution to the $K^-$ production rate from $\phi$ decays in nuclear collisions.

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