# Kaon and Phi Production in Pion-Nucleus Reactions at 1.7 GeV/$c^{\star}$

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**Abstract.** The production and properties of $K^+$, $K^-$ and $\phi$ in nuclear reactions $\pi^- + A$ ($A = C, W$) at a beam momentum of 1.7 GeV/$c$ has been studied with the HADES setup at SIS18/GSI. Of particular interest is the $K^-$ absorption in nuclear matter which should be driven by strangeness exchange processes on one ($K^-N \rightarrow Y\pi$) or more nucleons ($K^-NN \rightarrow YN\pi$). In this context, also the $\phi$ has to be taken into account, since $\phi$ decays into $K^+K^-$ pairs may substantially affect the measured $K^-$ abundance. A solid reference is needed to evaluate the $K^-$ absorption with in the nucleus and in this work we discuss the determination of this reference. A double ratio of $K^-/K^+(W)/K^-/K^+(C)$ is measured within the acceptance and compared to the reference.

## 1 Introduction

Pion-nucleus reactions allow for a quantitative study of the strange hadron production at nuclear saturation density. In this context, the FOPI collaboration demonstrated that the total $K^0$ production cross-section scales with the surface of the target nuclei ($\sigma = \sigma_{eff}\ A^{2/3}$, where $A$ denotes the mass number) [1]. Since kaons ($K^+$, $K^0$) do not undergo strong absorption processes within a nucleus, they can provide stringent constraints on the production mechanisms of strange hadrons. Contrary, the $K^-$ meson ($K^- = s\bar{u}$) properties in nuclear matter are more complex and less known. Several effects compete, the antikaon can be rescattered or be absorbed by nucleons and form baryonic resonances leading to the modification of its in-medium properties [2] [3]. This absorption strangeness exchange reaction can occur on one ($K^-N \rightarrow Y\pi$) or more nucleons ($K^-NN \rightarrow YN\pi$). A direct indication for the latter effect can be deduced from the comparison of the $K^-/K^+$ ratio measured in collisions with heavy targets like Tungsten ($W$) and lighter ones like Carbon ($C$). A peculiar role is played by the $\Lambda(1405)$ since this resonance is interpreted often as a molecular state partically composed of $\bar{K}N$ bound state [2].

## 2 The experiment

The **H**igh-**A**cceptance **D**i-**E**lectron **S**pectrometer (HADES) [4] is a fixed target experiment currently located at the SIS18 accelerator of the GSI Helmholtzzentrum in Darmstadt (Germany). It is composed of six identical sectors surrounding the beam axis covering almost the full azimuthal range and

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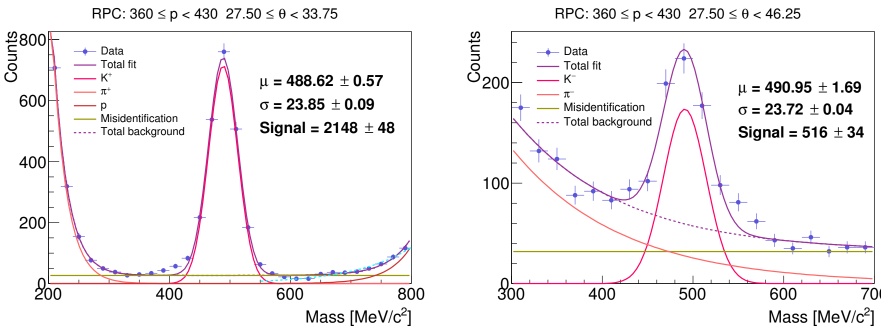


**Figure 1.** (Color online) Mass spectrum of $K^{+}$ (left) and $K^{-}$ (right) in a specific $p-\theta$ region (see legend) for the RPC in $\pi^{-}+C$ reactions. The $K^{+}$ signal is represented by a Gaussian (magenta line). The background is shown in pink (pions), red (protons) and green (misidentified particles), for details see text. The $K^{-}$ mass spectra is fitted with a composed function of a Gaussian for the signal (magenta line) and exponential function for the pions (pink line) combined with polynomial (green line).

polar angles from 18° to 85°. Two layers of **M**ultiwire **D**rift **C**hambers (MDC), in front and behind a superconducting magnet, allow for momentum reconstruction with a resolution of $\Delta p/p \approx 3\%$ and particle identification via dE/dx. In this experiment, the LVL1 trigger condition required a $T_0$ signal in the target detector [5] and a minimum multiplicity of two charged particle hits (M2) in the **M**ultiplicity and **E**lectron **T**rigger **A**rray (META) wall consisting of two time-of-flight detectors, RPC and TOF. Overall, $10\times10^{7}$ and $13\times10^{7}$ events have been collected in $\pi^{-}+C$ and $\pi^{-}+W$ at $p_{\pi^{-}}=1.7$ GeV/$c$, respectively.

## 3 Antikaon absorption

### 3.1 (Anti)Kaon abundance measured with HADES

Both charged kaon candidates have been identified with the energy loss information from the MDCs (details in [6]). The final (anti)kaon yield has been extracted by fitting the measured mass distribution, separately for the two time-of-flight detectors, RPC and TOF. High statistics allowed for a two-dimensional analysis in two different kinematic sets of variables $(p_T, y)$ and $(p,\theta)$. Figure 1 shows the mass spectrum for $K^{+}$ and $K^{-}$ corresponding to an interval in the RPC of $360 \le p$ [MeV/$c$] $< 430$ and $27.50 \le \theta$ [°] $< 33.75$ ($K^{+}$)/46.25 ($K^{-}$). The (anti)kaon signal is represented by a Gaussian on top of the background composed of polynominal combined with an exponential function for each background particle species. The width of the Gaussian was constrained to vary around the mean value of the width obtained from simulations. Further, in each phase space region the raw yield has been corrected for acceptance and efficiency based on simulations modelling the detector response in combination with GiBUU as an event generator.
Since the phase space coverage of the measured $K^{+}$ distribution is more extended compared to $K^{-}$, the double ratio $K^{-}/K^{+}(W)/K^{-}/K^{+}(C)$ was only extracted in the overlap regions within the HADES acceptance[1]. A double ratio of $K^{-}/K^{+}(W)/K^{-}/K^{+}(C) = 0.442 \pm (0.03)^{stat} \pm \left(^{+0.07}_{-0.04}\right)^{sys}$ has been extracted.

[1] $220 \le p$ [MeV/$c$] $< 570$, $15 \le \theta$ [°] $< 65$

### 3.2 (Anti)Kaon production based on cross-sections

In order to interpret the extracted double ratio $K^-/K^+(W)/K^-/K^+(C)$ in terms of the $K^-$ absorption, the influence on the double ratio caused by the different number of neutrons and protons in Tungsten ($A = 184, Z = 74, N = 110$) compared to Carbon ($A = 12, Z = 6, N = 6$) with the assumption of pure (anti-)kaon production without absorption has been taken into account. For this purpose all $K^+$ and $K^-$ production channels that can be accessed are listed in Tab. 1. As not all cross-sections have been measured at the presented beam momentum, a cross-section parametrization proposed by Sibirtsev *et al.* [9] has been adapted to extracted the cross-section for each individual channel at $p_{\pi^-} = 1.7$ GeV/$c$. It reads as follows:

$$\sigma = a\left(1 - \frac{s_0}{s}\right)^b \left(\frac{s_0}{s}\right)^c, \tag{1}$$

where $\sigma$ denotes the cross-section of a specific channel and $a, b, c$ the fit parameters. The channel dependent threshold and center-of -mass energy are given by $s_0$ and $\sqrt{s}$, respectively. The parametrization has been fitted to the available experimental measurements taken form Landolt-Börnstein [7] as shown for one example channel in Fig. 2. All measured cross-sections are shown as black points, whereas the fit function is represented as red solid curve together with the cross-section parametrization implemented in GiBUU [12] given by the yellow solid curve. Moreover, the blue dashed lines depicted the estimated cross-section for the incident pion beam momentum $p_{\pi^-} = 1.7$ GeV/$c$. It has to be mentioned that the experimental data for the channels $\pi^- + p \to \Sigma(1385)^- K^+$ and $\pi^- + n \to \Sigma^- + \pi^- + K^+$ is scarce, thus the extracted cross-sections are rather an upper limit.
The reference double ratio based on the pure production has been obtained by summing all elementary cross-sections ($\sigma_{fit}$ listed in Tab. 2) weighted with the relative neutron and proton contents. The scaling by $A^{2/3}$ [1] corresponding the effective number of nucleons on the surface of the nucleus cancels out. A double ratio based on the pure production of $K^-/K^+(W)/K^-/K^+(C) = 0.930 \pm 0.09$ has been extracted. For comparison also the double ratio has been deduced on the basis of the cross-sections ($\sigma_{\mathrm{GiBUU}}$ listed in Tab. 2) implemented in GiBUU with an value of $K^-/K^+(W)/K^-/K^+(C) = 0.966$.

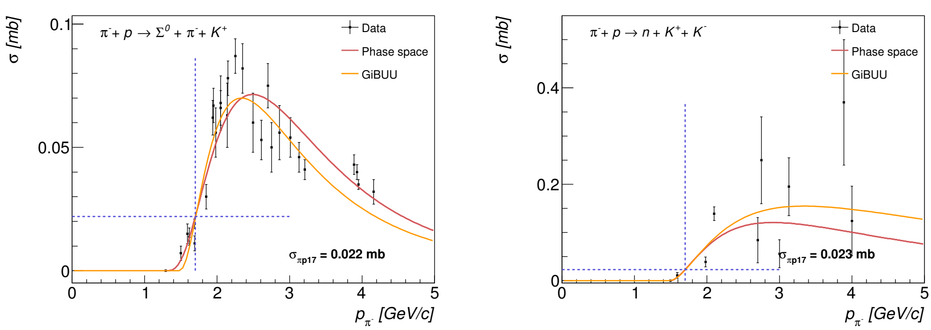


**Figure 2.** (Color online) Cross-section of $\pi^- + p \to \Sigma^- + \pi^0 + K^+$ (left) and $\pi^- + p \to n + K^+ + K^-$ (right) taken from the Landolt-Börnstein compilation [7] as function of the incident pion momentum. The red solid curve indicates the fit corresponding to a cross-section parametrization adapted from Sibirtsev *et al.* [9], while the yellow solid curve pictures the parametrization employed in GiBUU [12]. The blue dashed lines represent the suggested cross-section by the fit at $p_{\pi^-} = 1.7$ GeV/$c$.

**Table 1.** Production channels of $K^+$ and $K^-$ in pion-induced reactions with corresponding threshold momentum for the incident pions. The cross-section $\sigma_{fit}$ at $p_{\pi^-} = 1.7$ GeV/$c$ corresponding to a fit with a cross-section parametrization to experimental cross-sections measured at several energies compared to the cross-section parametrization implemented in GiBUU.

| | $K^+$ production | Threshold $p_{\pi^-}$ [GeV/$c$] | $\sigma_{fit}$ [mb] | $\sigma_{\mathrm{GiBUU}}$ [mb] |
|---|---|---|---|---|
| $\pi^- + p$ | $\Lambda\pi^- K^+$ | 1.144 | 0.0793 | 0.0908 [12] |
| | $\Lambda\pi^0\pi^- K^+$ | 1.407 | 0.0015 | |
| | $\Sigma^+\pi^-\pi^- K^+$ | 1.568 | 0.0003 | |
| | $\Sigma^0\pi^- K^+$ | 1.290 | 0.0220 | 0.0212 [12] |
| | $\Sigma^-\pi^+\pi^- K^+$ | 1.585 | $\approx 0$ | |
| | $\Sigma^-\pi^0 K^+$ | 1.290 | 0.0190 | 0.0152 [12] |
| | $\Sigma^- K^+$ | 1.035 | 0.1498 | 0.1564 [10] |
| | $\Sigma(1385)^0\pi^- K^+$ | 1.680 | $\approx 0$ | |
| | $\Sigma(1385)^-\pi^0 K^+$ | 1.680 | $\approx 0$ | |
| | $\Sigma(1385)^- K^+$ | 1.399 | $< 0.0693$ | |
| $\pi^- + n$ | $\Sigma^-\pi^- K^+$ | 1.296 | $< 0.0697$ | 0.0247 [12] |
| | $K^+/K^-$ production | | | |
| $\pi^- + p$ | $nK^+K^-$ | 1.495 | 0.0231 | 0.0224 [9] |
| | $n\phi(K^+K^-,\ BR \approx 48.9\%$ [8]) | 1.559 | 0.0274 | 0.0196 [11] |
| | $K^-$ production | | | |
| $\pi^- + p$ | $pK^0K^-$ | 1.497 | 0.0071 | 0.0110 [9] |

### 3.3 Summary

A comparison of the measured double ratio $K^-/K^+(W)/K^-/K^+(C)$ has been carried out to the reference double ratio based on the pure production. Accordingly, the double ratio extracted on the basis of the cross-section parametrization adapted from Sibirtsev *et al.* [9] and the one implemented GiBUU where averaged leading to a value of $K^-/K^+(W)/K^-/K^+(C) = 0.948 \pm 0.092$. The measured double ratio of $K^-/K^+(W)/K^-/K^+(C) = 0.442 \pm (0.03)^{stat} \pm \binom{+0.07}{-0.04}^{sys}$ is well below the reference directly indicating $K^-$ absorption in the heavy target Tungsten with respect to Carbon.

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