Measurement of charged and neutral kaons in Ar+Sc collisions at the NA61/SHINE experiment

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Abstract. NA61/SHINE is a large-acceptance fixed-target experiment conducted at the CERN SPS. The experiment has measured charged kaon production in 0-10% central Ar+Sc collisions at beam momenta of 13A, 19A, 30A, 40A, 75A, and 150A GeV/c. In this report, we present the measurements of K^0_S production and charged-to-neutral kaon ratio in 0-10% central Ar+Sc collisions at 75A GeV/c. The results are compared to the charged and neutral kaon production in other collision systems measured by NA61/SHINE, as well as to model predictions and data from other experiments.

1 Introduction

NA61/SHINE [1] is a fixed-target experiment located on the H2 beam line of the CERN SPS accelerator complex. Its primary detection system comprises four Time Projection Chambers (TPCs), which enable precise measurement of particle momenta and provide particle identification through specific energy loss (dE/dx). Additionally, two Time-of-Flight (ToF) walls improve kaon identification capabilities (*tof* measurement). The TPC setup enables particle detection at transverse momenta as low as $p_T = 0$ GeV/c across a wide range of forward rapidities. A high-resolution hadron calorimeter, the Projectile Spectator Detector, measures forward-going energy and is used to determine the centrality of nuclear collisions.

The primary goal of the strong interaction program of the NA61/SHINE experiment is to discover the critical point of strongly interacting matter, study the properties of the onsets of deconfinement and fireball, and measure the open charm production. To accomplish this goal, a two-dimensional scan of the phase diagram of strongly interacting matter is conducted by varying the beam momentum (13A-150/158A GeV/c) and the size of the colliding nuclei (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb).

2 Kaon production

NA61/SHINE has measured the inclusive spectra and mean multiplicities of $K^\pm$ mesons in the 10% most central Ar+Sc collisions at beam momenta of 13A, 19A, 30A, 40A, 75A, and 150A GeV/c (corresponding to $\sqrt{s_{NN}}$ = 5.12, 6.12, 7.62, 8.77, 11.9 and 16.8 GeV) [2]. Charged kaons were identified by dE/dx and combined *tof*-dE/dx method. At high momenta, in the region of the relativistic rise, the dE/dx measurement alone was sufficient to identify

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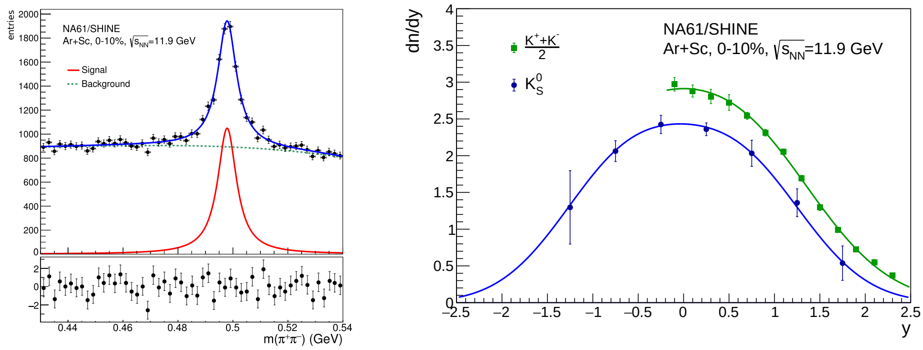

Figure 1. Fitted invariant mass distribution of K^0_S candidates in rapidity - transverse momentum bin $y \in (-1.0, -0.5)$, $p_T \in (1.2, 1.5)$ GeV/c. The bottom panel shows the difference between the experimental data and the fitted (signal+background) function, divided by the experimental uncertainty (left). The rapidity spectrum of K^0_S mesons in 0-10% central Ar+Sc collisions at 75*A* GeV/c is shown by blue circles [5]. Green squares represent the averaged spectrum of charged kaons [2]. Total uncertainties are drawn. Blue and green curves show the result of double Gaussian fit (Eq. 1) to the K^0_S and averaged fit for charged kaons spectra, respectively (right).

charged kaons. At lower momenta, where the bands for different particle species overlap, the additional measurement of *tof* was used for unambiguous kaon identification. These two methods cover most of the relevant rapidity and transverse momentum space, especially the mid-rapidity region of K^+ and K^- spectra. The yields of charged K mesons at mid-rapidity in the 10% most central Ar+Sc collisions at beam momentum of 75*A* GeV/c were determined in the interval of collision center-of-mass rapidity $0.0 < y < 0.2$ and amount to $(\mathrm{d}n/\mathrm{d}y)(K^+)_{y\approx 0} = 3.732 \pm 0.016\ (stat) \pm 0.148\ (sys)$ and $(\mathrm{d}n/\mathrm{d}y)(K^-)_{y\approx 0} = 2.029 \pm 0.012\ (stat) \pm 0.069\ (sys)$.

K^0_S mesons were identified by the characteristic topology of their decay into charged pions ($K^0_S \rightarrow \pi^+ + \pi^-$, with a branching ratio BR = 69.2%). The identification process involved pairing all positively charged pion candidates with negatively charged ones. These pairs were then tracked backward through the NA61/SHINE magnetic field, and the minimum distance of closest approach (DCA) between the particles was determined. A pair was considered a K^0_S candidate if the DCA was less than 1 cm. The invariant mass of the resulting decay particle pairs forms a distribution that contains both the K^0_S signal and background contributions, such as those from Λ decays, photon conversions, and random particle crossing. A K^0_S signal appears as a peak on top of a smooth background. The raw number of K^0_S in different rapidity - transverse momentum bins was determined by fitting the invariant mass spectrum. The fit function consisted of a Lorentzian to describe the K^0_S signal and a third-order Chebyshev polynomial to account for the background. An example of the invariant mass distribution, together with the signal and background fits, is shown in Fig. 1 (left). The raw number of K^0_S was corrected for losses due to the geometrical acceptance, reconstruction efficiency, and selection criteria applied in the analysis. The corrections were based on simulated Ar+Sc events produced by the EPOS [3] event generator. The simulated particles were tracked through the NA61/SHINE detector using the GEANT framework [4]. The simulated events were reconstructed with the same software as the experimental events and the same selection criteria were applied. The reliability of the K^0_S reconstruction and correction procedure was validated by studying the K^0_S lifetime distributions in seven rapidity bins, for details see Ref. [5]. The

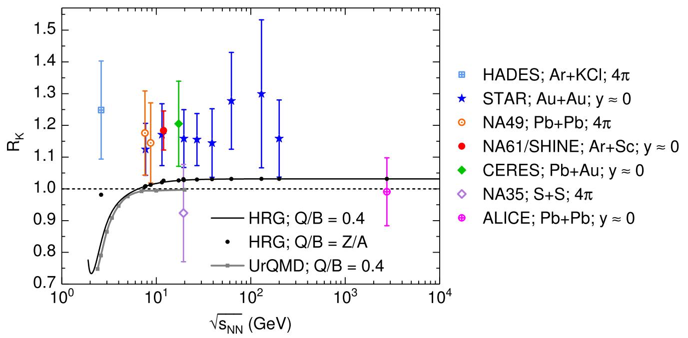

Figure 2. Charged-to-neutral kaon ratio as a function of collision energy. Experimental data are shown by symbols with total uncertainties. HRG baseline for electric-to-baryon charge $Q/B = 0.4$ is shown by a black line. HRG baseline for Q/B values specified accordingly to given types of colliding nuclei is represented by black dots. UrQMD model results are shown by grey squares. Figure from Ref. [7] with later changes.

extracted mean K^0_S lifetimes agree within uncertainties with the PDG [6] value in all rapidity bins indicating a good quality of the analysis.

The double-differential yield of K^0_S meson in 0-10% central Ar+Sc collisions at 75A GeV/c was calculated in seven rapidity bins in the range $-1.5 < y < 2.0$ and nine transverse momentum bins spanning $0.0 < p_T < 2.7$ GeV/c. The transverse momentum spectra were fitted using an exponential function $f(p_T) = A \cdot p_T \cdot \exp(-\sqrt{p_T^2 + m_0^2}/T)$, where A is a normalisation factor, m_0 is the mass of K^0_S, and T represents the inverse slope parameter. The yield of K^0_S in each rapidity bin was determined by integrating the fitted exponential function. The resulting rapidity spectrum, shown in Fig. 1 (right), was fitted with a double-Gaussian function:

$$f(y) = A_1 \cdot \exp\left(-\frac{1}{2}\frac{(y-\mu)^2}{\sigma^2}\right) + A_2 \cdot \exp\left(-\frac{1}{2}\frac{(y+\mu)^2}{\sigma^2}\right), \tag{1}$$

where A_1 and A_2 are the normalisation factors, μ represents the displacement of each Gaussian from $y = 0$, and σ is the standard deviation. The mean multiplicity of K^0_S meson, calculated as the integral of fitted double-Gaussian function, is $\langle K^0_S \rangle = 6.49 \pm 0.10\ (stat) \pm 0.83\ (sys)$.

The yield of K^0_S meson at mid-rapidity, determined from the fit at $y = 0$, was found to be $(\mathrm{d}n/\mathrm{d}y)_{y\approx 0} = 2.433 \pm 0.027\ (stat) \pm 0.102\ (sys)$.

3 Charged-to-neutral kaon ratio

In Ar+Sc collisions, an approximately equal abundance of charged and neutral kaons is expected as Ar and Sc nuclei are nearly isospin symmetric (valence quarks u = d within 6%), for details see Ref. [5] and references therein. However, experimental data from NA61/SHINE [5] show a significant difference. The rapidity distribution of K^0_S mesons, compared with the averaged distribution of K^+ and K^- mesons, Fig. 1 (right), reveals a much higher yield of charged kaons across the entire rapidity range. At mid-rapidity, the charged-to-neutral kaon ratio defined as $R_K = (K^+ + K^-)/(2K^0_S)$ was found to be 1.184 ± 0.061.

In Fig. 2, this charged-to-neutral kaon ratio was compared with a compilation of results on K^+, K^- and K^0_S production from other experiments and predictions from the Ultrarelativistic

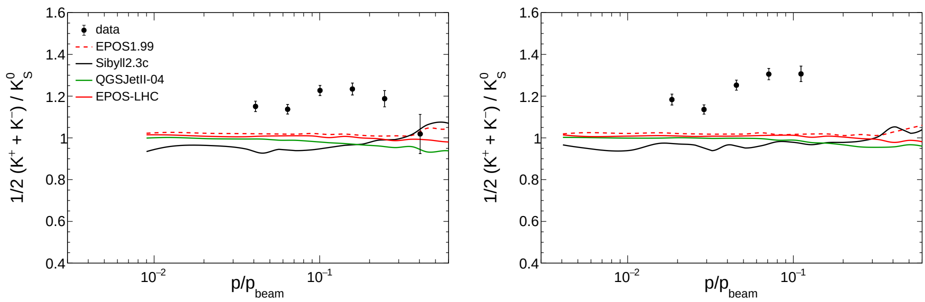

Figure 3. Charged-to-neutral kaon ratio in π^-+C reactions at 158 GeV/c (left) and 350 GeV/c (right) plotted as a function of scaled laboratory momentum p/p_{beam}, adopted from Ref. [10]. Only statistical uncertainties are drawn, while systematic uncertainties are estimated to be 5-10%.

Quantum Molecular Dynamics (UrQMD) [8] and Hadron Resonance Gas (HRG) [9] models. While data from other experiments, despite their large uncertainties, support NA61/SHINE results, both models fail to describe the observed charged-to-neutral kaon ratio.

Ratios $R_K > 1$ were also observed in π^-+C collisions at beam momenta of 158 and 350 GeV/c. These measurements, shown in Fig. 3, were compared with the predictions of several microscopic models. None of the models can reproduce the observed charged-to-neutral kaon ratio.

4 Summary

NA61/SHINE has measured charged kaon production in 0-10% central Ar+Sc collisions at several beam momenta: 13A, 19A, 30A, 40A, 75A, and 150A GeV/c. K^0_S production has been measured in 0-10% central Ar+Sc collisions at 75A GeV/c. At this beam momentum, the ratio of charged-to-neutral kaons, defined as $R_K = (K^+ + K^-)/(2K^0_S)$, was found to be 1.184 ± 0.061. The $R_K > 1$ has been measured also in π^-+C collisions at 150 and 350 GeV/c. The UrQMD and Hadron Resonance Gas models do not reproduce the experimental results on charged-to-neutral kaon ratio in A+A collisions. Models fail to describe charged-to-neutral kaon ratio also for small asymmetric π^-+C systems.

References

[1] N. Abgrall *et al.* [NA61/SHINE Collab.], JINST **9**, P06005 (2014).

[2] H. Adhikary *et al.* [NA61/SHINE Collab.], Eur. Phys. J. C **84**, 416 (2024).

[3] K. Werner, Nucl. Phys. Proc. Suppl. **175-176**, 81 (2008).

[4] Brun, R. Hagelberg, M. Hansroul, and J. C. Lassalle, Tech. Rep. CERN-DD-78-2-REV, CERN-DD-78-2, CERN, Geneva (1978).

[5] H. Adhikary *et al.* [NA61/SHINE Collab.], arXiv:2312.06572 [nucl-ex].

[6] S. Navas *et al.* [Particle Data Group Collab.], Phys. Rev. D **110**, 030001 (2024).

[7] W. Brylinski, M. Gazdzicki, F. Giacosa, M. Gorenstein, R. Poberezhnyuk, S. Samanta, and H. Stroebele, arXiv:2312.07176 [nucl-th].

[8] M. Bleicher *et al.*, J. Phys. G **25**, 1859 (1999).

[9] V. Vovchenko and H. Stoecker, Comput. Phys. Commun. **244**, 295 (2019).

[10] H. Adhikary *et al.* [NA61/SHINE Collab.], Phys. Rev. D **107**, 062004 (2023).