Large isospin symmetry violation in kaon production?

Wojciech Brylinski[1,*]
for the NA61/SHINE Collaboration

[1]Warsaw University of Technology

Abstract. The recent measurements of kaon production in Ar+Sc collisions at 75*A* GeV/*c* ($\sqrt{s_{NN}}$ = 11.94 GeV) performed by NA61/SHINE at the CERN SPS resulted in determining the ratio of charged to neutral kaons to be 1.26 ± 0.06. The result, well above unity, cannot be explained by models accounting for known isospin symmetry violating processes. This contribution will present the experimental details of this intriguing result. It will also compare it to the world data on charged to neutral kaon ratio in nucleus-nucleus collisions.

1 Introduction

SPS Heavy Ion and Neutrino Experiment (SHINE) [1] is a fixed-target experiment operating at the Super Proton Synchrotron (SPS) at the European Organization for Nuclear Research (CERN). The main physics motivation of the NA61/SHINE is to study the properties of the phase transition between hadronic matter and quark-gluon plasma. Within this program, NA61/SHINE performed a two-dimensional scan in collision energy (13*A*–150(8)*A* GeV/*c*) and system size (p+p, Be+Be, Ar+Sc, Xe+La, Pb+Pb).

The NA61/SHINE detector is a multi-purpose spectrometer optimised to study hadron production in various types of collisions. The main subdetectors of the whole setup are the Time Projection Chambers (TPC). Two Vertex-TPCs (VTPCs), located in the magnetic field, together with two large volume Main-TPCs (MTPCs) are main tracking devices and are able to register a large number of particle tracks (up to 1500 in central Pb+Pb collisions). Such setup provides excellent capabilities in charged particles momenta measurement and allows for the particles identification complemented by the information from the Time-of-Flight (ToF) detectors. The last detector on the beamline is Projectile Spectator Detector (PSD), which measures the energy of spectators. This information is used to determine the centrality in A+A collisions with a very good accuracy. Beam particles are measured by an array of beam detectors. They are used for the beam trajectory measurement and the identification of beam particles as well as triggering the data acquizition system of the whole spectrometer.

2 Kaon analysis in Ar+Sc collisions

The charged kaons were identified based on the measurement of energy loss along the particle trajectory in Time Projection Chambers combined with the measurement of Time-of-Flight. The details of the charged kaons analysis can be found in Ref. [2]. The K^0_S mesons are

*e-mail: wojciech.brylinski@cern.ch

neutral particles and can be studied by the analysis of the charged decay products that can be detected. The most abundant decay channel of K_S^0 with branching ratio of 69.2% is the decay into a pair of charged pions. The neutral kaon analysis was based on the reconstruction of invariant mass of pairs of particles that are assumed to be candidates for decay products. The obtained results were corrected for the detection and reconstruction inefficiencies using simulated data. The analysis details can be found in Ref. [3].

3 Charged-to-neutral kaon ratio

Strong interactions preserve approximately isospin (I) and its third component (I_3), which, among others, for collisions of $N = Z$ nuclei (N – number of neutrons, Z – number of protons) corresponds to equivalence in the production of new pairs of $u - \overline{u}$ and $d - \overline{d}$ quarks [4]. Following Smushkevich rule, for all particles involved in isospin-conserving reactions, all members of isospin multiplets are produced in equal numbers if and only if the initial population is uniform [5–7]. Thus, for an electric-to-baryon charge ratio (Q/B; $Q \equiv Z$) equal to 1/2 ($I = I_3 = 0$) and in the case of exact isospin symmetry we expect the following relations between kaon multiplicities: $K^+(u\overline{s}) = K^0(d\overline{s})$ and $K^-(\overline{u}s) = \overline{K}^0(\overline{d}s)$. By summing up the equations one obtains: $K^+ + K^- = K^0 + \overline{K}^0$. The K^0 and $\overline{K}^0$ mesons are not directly measured in detectors since the physical neutral states are the K_S^0 and K_L^0. Neglecting a very small effect of the CP violation, the production of K_S^0 should be given by: $K_S^0 = \frac{K^0 + \overline{K}^0}{2}$. Therefore, we expected the relation between multiplicities: $K_S^0 = \frac{K^+ + K^-}{2}$.

The left panel of Fig. 1 shows the comparison of rapidity spectrum of neutral (K_S^0) with the average spectrum of charged (K^+ and K^-) mesons [2] ($K^{+/-} = \frac{K^+ + K^-}{2}$). A similar plot but for transverse momentum spectra is presented in the right panel of Fig. 1. Additionally, for transverse momentum spectra, the R_k ratio is plotted, where $R_k = \frac{K^{+/-}}{K_S^0}$. A significant difference between $K^{+/-}$ and K_S^0 yields is observed for both rapidity and transverse momentum spectra.

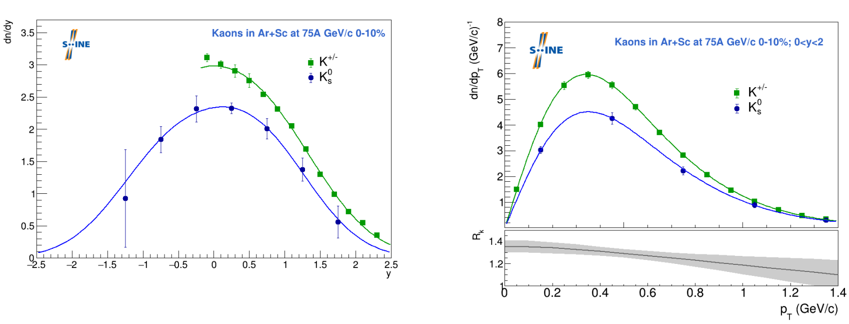

Figure 1. *Left*: Comparison of rapidity spectrum of neutral (K_S^0: NA61/SHINE preliminary) with the average spectrum of charged (K^+ and K^-) mesons in 0–10% central Ar+Sc collisions at 75A GeV/c. The total uncertainties are plotted and calculated as the square root of the sum of squared statistical and systematic uncertainties ($\sqrt{\text{stat}^2 + \text{sys}^2}$). For charged kaons [2], the total uncertainties were calculated separately for positively charged and negatively charged kaons and then propagated. *Right*: same as *left* but for transverse momentum spectra.

Figure 2 presents the compilation of available data on the ratio of charged to neutral kaons as a function of collision energy. The systematic excess of the production of charged kaons is visible in the presented nucleus-nucleus data. The world data, having large uncertainties of individual points, support the NA61/SHINE finding.

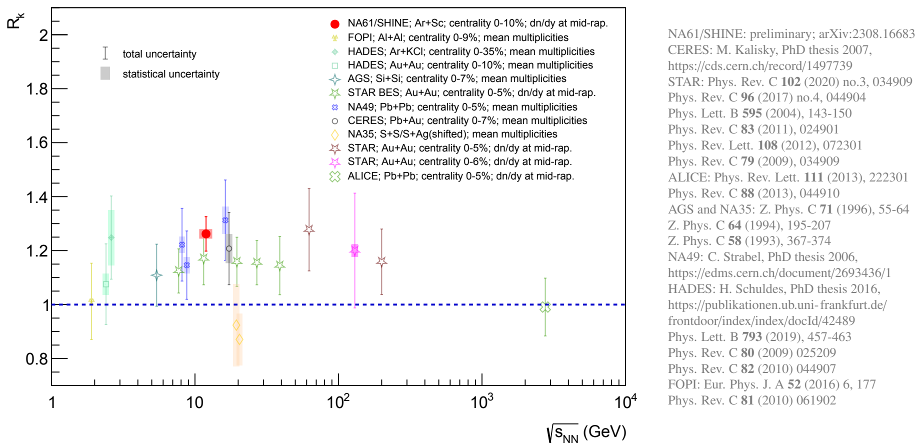

Figure 2. Compilation of the available data on the ratio of charged to neutral kaons as a function of collision energy. The measurement from NA61/SHINE is shown as a red dot. The world data come from references given in the rigth panel of the figure.

The comparison of the charged-to-neutral kaon ratio with the predictions of the Hadron Resonance Gas (HRG) model [8] is presented in Fig. 3 (taken from Ref. [9]). The black line shows the HRG baseline for electric-to-baryon charge $Q/B = 0.4$. For Ar+Sc collisions $Q/B = 0.45$ (Ar) and $Q/B \approx 0.47$ (Sc), whereas $Q/B \approx 0.4$ corresponds to Pb or Au nuclei. The black dots in Fig. 3 represent the HRG baseline for Q/B values specified according to the given types of colliding nuclei.

The prediction of HRG takes into account a set of known effects that violate isospin symmetry, or preserve it but still can lead to a deviation of R_k from unity [6]. For example, the somewhat smaller mass of charged than neutral kaons leads to a small increase of R_k. At the same time, the somewhat larger number of neutrons than protons in Ar and Sc nuclei leads to a small decrease of R_k. All the considered known effects are discussed in detail in Ref. [9]. The HRG predicted deviation from the expected value of $R_k = 1$ is significantly smaller than for the experimental data. Thus, the presented result is to be considered as evidence for effects that go beyond the ones predicted by the HRG model.

4 Summary

This contribution presents unexpected excess of charged over neutral kaon production in central Ar+Sc collisions at the beam momentum of 75*A* GeV/*c*. It is at present a subject of active scrutiny whether this result could be an indication of a violation of isospin symmetry being significantly stronger than commonly assumed for high-energy nuclear collisions.

Acknowledgements: This work was supported by the Polish Ministry of Science and Higher Education (grant WUT ID-UB), the Norwegian Financial Mechanism 2014–2021 (grant 2019/34/H/ST2/00585), the Polish Minister of Education and Science (contract No. 2021/WK/10).

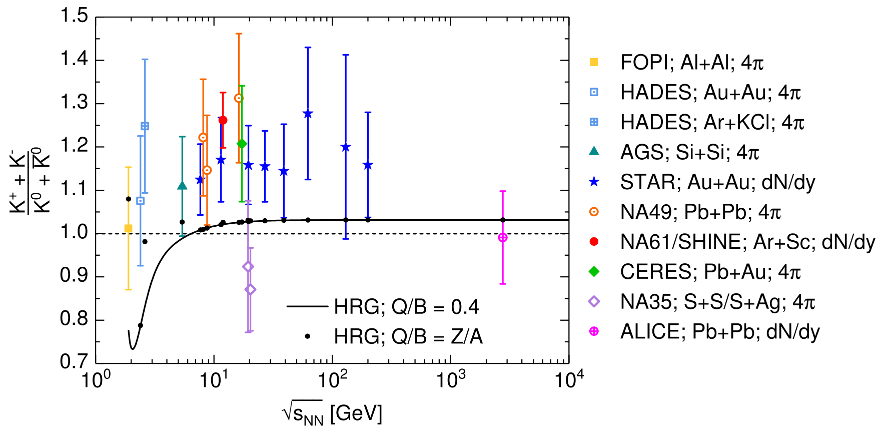

Figure 3. Comparison of charged-to-neutral kaon ratio ($K^0 + \overline{K}^0$; in HRG equal $2K^0_S$) with predictions of the Hadron Resonance Gas model [8]. The black line shows the HRG baseline for electric-to-baryon charge ratio $Q/B = 0.4$. Black dots represent the HRG baseline for Q/B values specified according to the given types of colliding nuclei. Figure taken from Ref. [9].

References

[1] N. Abgrall *et al.* [NA61 Collaboration], JINST **9**, P06005 (2014) doi:10.1088/1748-0221/9/06/P06005 [arXiv:1401.4699 [physics.ins-det]].

[2] H. Adhikary *et al.* [NA61/SHINE], [arXiv:2308.16683 [nucl-ex]].

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

[4] P. B. Pal, "An introductory course of particle physics", CRC Press, Taylor & Francis Group (2015).

[5] I. Smushkevich, Dokl. Akad. Nauk SSSR 103 (1955), 235.

[6] C. G. Wohl, Am. J. Phys. 50 (1982) 748–753.

[7] A. J. MacFarlane, G. Pinski, and G. Sudarshan, Phys. Rev. 140 (1965) B1045.

[8] V. Vovchenko, H. Stoecker, Comput. Phys. Commun. 244 (2019) 295–310, [arXiv:1901.05249 [nucl-th]].

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