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2010 J. Phys. G: Nucl. Part. Phys. 37 094036

(http://iopscience.iop.org/0954-3899/37/9/094036)

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **37** (2010) 094036 (6pp) doi:10.1088/0954-3899/37/9/094036

# Strangeness production at (sub)threshold energies

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Received 17 January 2010
Published 6 August 2010
Online at stacks.iop.org/JPhysG/37/094036

**Abstract**

Strange particles allow us to probe the properties of hot and dense baryonic matter. At incident energies close to the production threshold medium effects on the strange hadrons are magnified. New data obtained with the recently completed FOPI upgrade are presented for the system Ni+Ni at 1.91 $A$ GeV and discussed in comparison to earlier findings. Special emphasis is put on the search for multibaryonic strange bound states, of which the $\Lambda p$-channel is analyzed in detail.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Modifications of hadron properties in dense baryonic matter are a current subject of intensive research in hadron physics. Various theoretical approaches [1–3] agree qualitatively on predicting, for example, modifications of masses and coupling constants for kaons and anti-kaons. Due to the density dependence of the $K$N($\overline{K}$N) potential, the $K^-$ effective mass is expected to drop, whereas the mass of $K^+$ mesons is predicted to rise with increasing density of nuclear matter. Already two decades ago, Kaplan and Nelson [4] pointed out that due to additional attractive interactions with the surrounding nucleons a condensation of anti-kaons ($K^-$) may take place in a dense baryonic environment as encountered in the interior of neutron stars.

The strength of the $K^-$-nucleon potential might give rise to a new class of bound states [5, 6] with quite exotic properties. These bound states are called kaonic clusters and are being searched for in stopped $K^-$-beams [7, 8] and in $pp$-reactions [9]. Due to their predicted large central densities and the large compression reached in heavy-ion reaction their production might be favored in heavy-ion reactions [10] and therefore a complementary program was started to look for bound multibaryonic strange states in heavy-ion reactions [11].

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[1] A list of members of the FOPI Collaboration is available at http://www-fopi.gsi.de/people/index.html.

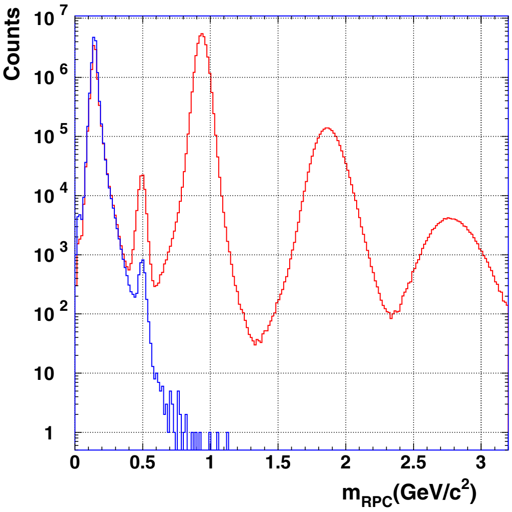

**Figure 1.** Reconstructed masses for a momentum range up to 1.0 GeV$/c$ making use of CDC–RPC matches. Positively charged particles are plotted in the upper histogram (red); negative ones are shown in the lower one (blue). Mass peaks for pions, kaons, proton, deuterons and triton are clearly visible. Positively charged kaons exhibit a signal-to-background ratio of better than 10.

In the following, new data obtained with the FOPI detector in 2008 at the SIS18 accelerator of GSI are shown for the reaction Ni+Ni at an incident energy of 1.91 $A$ GeV elucidating some key aspects of strangeness physics in the threshold energy range.

## 2. Experiment: FOPI—phase III

In order to allow the detection of strange particles the FOPI detector was upgraded with the installation of a new time-of-flight barrel covering the polar angle range $35^\circ < \Theta < 60^\circ$ based on Multigap Resistive Plate Chambers (MRPC) [12] in 2006. Since then this detector was used in major data-taking runs for which the first result has now become available. The performance in identifying the emitted particles is depicted for the reaction Ni+Ni at an incident energy of 1.91 $A$ GeV in figure 1 where the mass values are shown that are calculated from the momentum reconstructed in the central drift chamber (CDC) and the velocity measured in the MRPC barrel. The time resolution and the granularity are sufficient to separate positively (negatively) charged kaons with a signal-to-background ratio in excess of 10 when the maximum momentum is limited to 1.0 (0.8) GeV$/c$, respectively.

## 3. Differential kaon flow

The superb kaon identification of the MRPC barrel allows us to perform differential flow analysis of these rare particles and thus to continue the effort to determine the in-medium potential for kaons and antikaons [13]. The analysis has progressed to an extent that first surprising data on the differential sideflow of kaons can be shown.

In figure 2 the first Fourier coefficients $v_1$ [14] are plotted as a function of the normalized rapidity for kaon and protons for two different centralities. The direction of the reaction plane was determined by the transverse momentum method [15] making use of particles

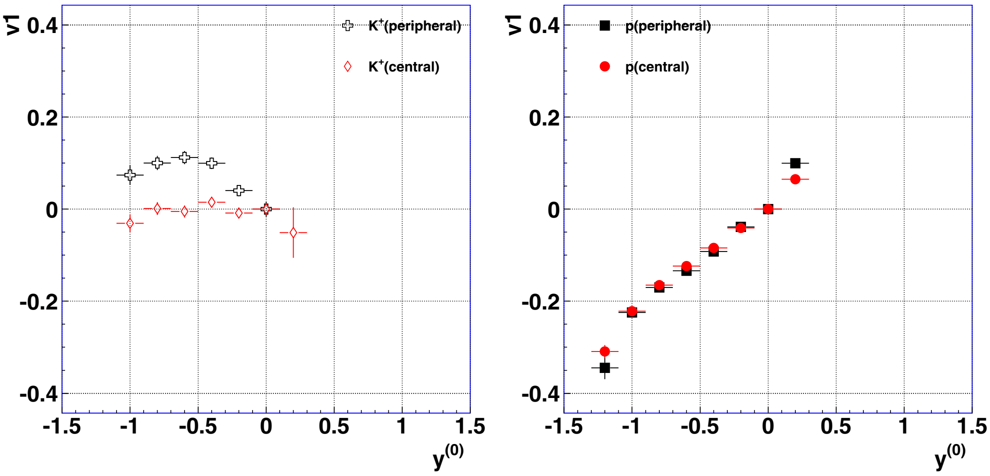

**Figure 2.** Sideflow of kaons and protons in the reaction Ni+Ni at an incident energy of 1.91 *A* GeV as a function of the normalized rapidity $y^{(0)} = y/y_{CM} - 1$. The first Fourier coefficients $v_1$ are plotted for two different centrality bins for kaons (left panel) and protons (right panel). Black data points are obtained for peripheral collisions corresponding to a mean impact parameter of 6 ± 1 fm; the red ones for central collisions with a geometrical impact parameter $b < 3$ fm. The $v_1$-values are obtained within the acceptance of the CDC; for details see the text.

detected in the forward wall of FOPI only in order to avoid autocorrelations. The data are corrected for the finite reaction plane resolution making use of the Ollitrault formalism [16]. For better comparability with different reaction plane reconstruction methods the $v_1$-data were shifted such that the mean $v_1$-value at midrapidity could vanish as required by symmetry. The centrality selection was chosen such that for both centrality bins the proton flow is approximately the same. Thus the event samples differ by the amount of stopping and the maximum density reached within the collision leading to the same sideward deflection. While the kaon data in the central event sample confirm quantitatively our earlier findings [17, 18], the large sideflow in the most peripheral data sample is rather unexpected: at a normalized rapidity of $y^{(0)} \approx 0.5$ the antiflow of the kaons is as large in magnitude as the flow of the protons. Tentatively this effect can be attributed to the strong momentum dependence of the kaon potential. This hypothesis awaits its confirmation/rejection by transport model calculations.

In order to compare to the data shown in figure 2, model calculations have to take into account the acceptance of the detector, which is limited for this detailed analysis to the acceptance of the CDC covering a polar angle range of $26^\circ < \Theta_{\mathrm{lab}} < 120^\circ$. For kaons additional constraints have to be put on the momenta necessary to obtain sufficient particle identification in the data. In the polar angular range from $30.5^\circ < \Theta_{\mathrm{lab}} < 52^\circ$ (MRPC acceptance) kaons are included up to a momentum of 1.0 GeV, and in the range $53^\circ < \Theta_{\mathrm{lab}} < 120^\circ$ (plastic barrel acceptance) the laboratory momentum is limited to 0.5 GeV. The angular limits correspond to the so-called shifted target geometry, where the target was placed 40 cm upstream of its nominal position in the FOPI apparatus.

The available data sample also allows the reconstruction of the $K^-$-flow. However, this analysis is much more difficult due to the very low yield of $K^-$ that is at the 3% level of $K^+$-production. The analysis is in progress.

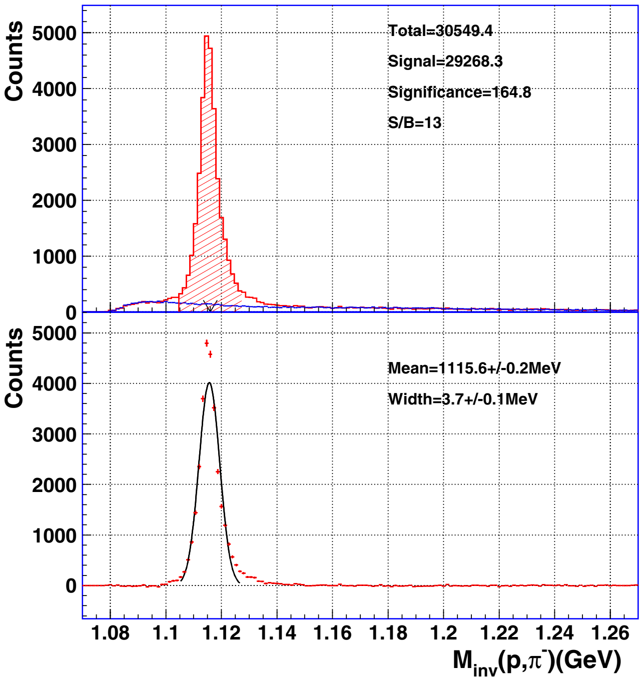

**Figure 3.** Reconstructed invariant mass of off-vertex pion–proton pairs. A minimal distances of 1.9 (0.6) cm was required for pions (protons) in combination with a pointing angle cut of $|\Delta\phi| < 2^\circ$ and a transverse flight path of at least 4 cm. In the upper panel 29 000 candidates are reconstructed in $5.6 \times 10^7$ events in the reaction Ni+Ni at 1.91 $A$ GeV subtracting the mixed event background (blue histogram) from the correlated pairs (red histogram). The signal distribution (lower panel) exhibits a mass resolution of $\sigma_M = 3.7$ MeV. Within a $2.5 \times \sigma_M$ interval around the nominal mass (hatched area in the upper panel) a signal-to-background ratio of 13 is obtained.

## 4. Λ-baryon reconstruction

Strangeness physics in the threshold energy range is dominated by associate production underlining the importance to investigate hyperons in the same event samples as kaons. Phase space distributions of Λ-baryons are already published from earlier experiments [19]. With the current setup, high statistics data samples can be obtained with very high purity as shown in figure 3 where a Λ-baryon signal is shown with a signal-to-background ratio of 13. The mean value of the reconstructed invariant mass peak with the current calibration amounts to $M = 1.1156 \pm 0.0002$ GeV in very good agreement with the PDG values. Due to the consistency checks allowed by the presence of the new MRPC barrel, the calibration of the CDC could be improved, so a Gaussian width of $\sigma_M = 3.7$ MeV is now achieved for the Ni+Ni data of the 2008 run.

The purities shown in figure 3 are necessary for a clean study of Λ-baryon flow and for the correlation analysis presented in the next section.

## 5. Proton–Λ correlations

In our previous high statistics data samples, besides Λ–deuteron [11] we had analyzed Λ–proton correlations [21, 22] showing a clear signal at an invariant mass of $M = 2.13 \pm$

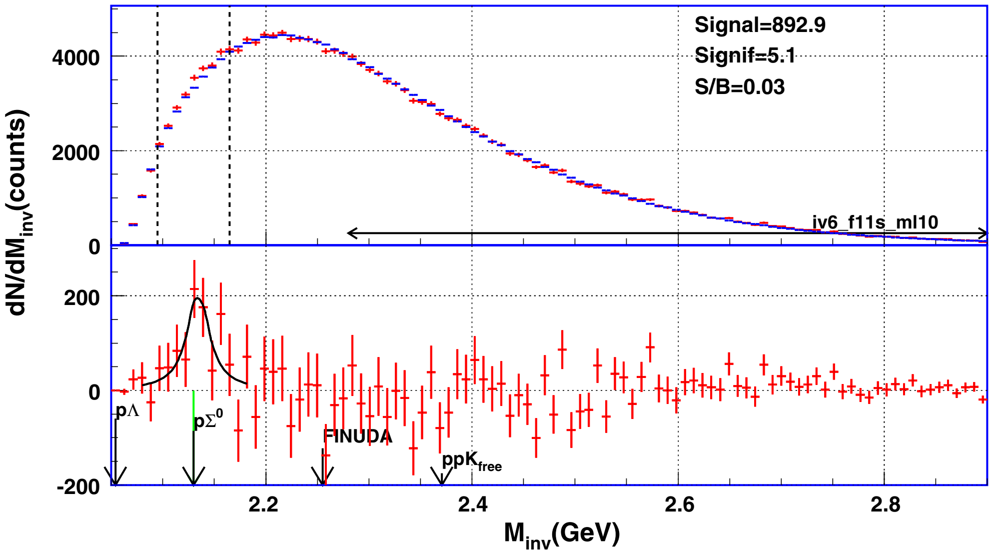

**Figure 4.** Reconstructed invariant mass of Λ–proton pairs. The solid histogram and crosses denote the data (red) and the scaled mixed-event background (blue), respectively (upper panel). Both distributions were normalized over the range indicated by the horizontal arrow. The lower panel shows the difference and an excess at a mean value $M(p\Lambda) = 2.134 \pm 0.004$ GeV with a width of $\Gamma = 26 \pm 14$ MeV (statistical errors only). The statistical information (signal strength, significance and signal-over-background ratio) is extracted in the mass range limited by the vertical dashed lines shown in the upper panel.

0.02 GeV for the reactions studied so far: Ni+Ni at 1.93 *A* GeV and Al+Al at 1.91 *A* GeV. Note that in these analyses the combinatorial background is reconstructed by using the same techniques as were used for the $\Sigma^*$ measurement [20] that could be clearly identified in Λ–charged pion correlations. The existence of a peak structure in the Λ–proton correlation is confirmed by the latest data taken with the FOPI apparatus and shown in figure 4. The parameters of the peak structure (mean, width and yield) are consistent within statistical errors with the previous findings [21, 22]. The reconstructed yield amounts within the acceptance to 3% of the Λ-yield and is not distributed according to thermal phase space. In figure 4 only proton–Λ pairs with a combined rapidity of $y_{\Lambda p} < 0.65$ are shown. No significant structure was seen at midrapidity.

The location of the peak at $M(p\Lambda) = 2.134$ GeV agrees within the resolution with the proton-$\Sigma^0$ threshold at 2.1309 GeV and thus drives the hypothesis that the structure is caused by a deuteron-like configuration of a proton and a hyperon. Similar structures have been reported in elementary hadron reactions [23–25]. However, the interpretation of the peak structure is still controversial since strong dependences on the kinematics were observed. With our accumulated high statistics FOPI data we now confirm the existence of the structure in heavy-ion collisions where essentially no kinematic constraints exist due to the strong thermalization of the reaction systems.

As indicated by the arrow markers in figure 4 the structure observed in the heavy-ion data is clearly different from the one seen in $K^-$absorption in the FINUDA experiment that is considered a candidate for a deeply bound kaonic state. However, the datasets are not necessarily contradicting each other since (a) FINUDA has almost no acceptance for an invariant mass of 2.13 GeV and (b) the production yield of deeply bound states could be much lower than the one for the observed deuteron-like strange dibaryon.

## 6. Conclusion

New data have been presented by making use of the FOPI phase III setup at GSI elucidating the properties of a strange particle in dense baryonic matter. For the first time a strong antiflow component for $K^+$ is seen for peripheral Ni+Ni reactions at 1.91 $A$ GeV pointing to a strong momentum dependence of the kaon–nucleus potential. The special role of the strange quark is visible in the formation of strange dibaryonic systems. Evidence is presented for the existence of a quasi bound state at an invariant mass of 2.134 ± 0.004 GeV. Further investigations are necessary to clarify the nature of this state and/or the existence of even heavier multibaryonic strange states. More data are available from the 2009 measurement campaign of FOPI where more than $10^8$ events were recorded for the reactions Ni+Pb at an incident energies of 1.91 $A$ GeV and Ru+Ru at 1.65 $A$ GeV opening new possibilities to study hadronic states in the hadronic environment of a heavy-ion collision.

## Acknowledgments

This work was supported by the German BMBF under contract no 06HD190I, by the Korea Science and Engineering Foundation (KOSEF) under grant no F01-2006-000-10035-0, by the mutual agreement between GSI and IN2P3/CEA, by the Hungarian OTKA under grant no 47168, within the Framework of the WTZ program (Project RUS 02/021), by DAAD (PPP D/03/44611), by DFG (Projekt 446-KOR-113/76/04) and by the EU 6th Framework Program, Integrated Infrastructure: Strongly Interacting Matter (Hadron Physics), contract no RII3-CT-2004-506078.

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