Dilepton and strangeness production probed with HADES

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With the High Acceptance Di-Electron Spectrometer (HADES) at GSI we have studied dilepton production in the few-GeV energy regime in various collisions systems, from elementary NN, over pA, up to the medium-heavy Ar+KCl system. We have thus confirmed the puzzling results of the former DLS collaboration at the Bevalac. While we have traced the origin of the excess pair yield in CC collisions to elementary pp and pn processes, in our Ar+KCl data a contribution from the dense phase of the collision has been identified. Together with the e^+e^- pairs, we have also obtained in the Ar+KCl system at 1.76 AGeV a high-statistics data set on open and hidden strangeness, i.e. $K^{\pm}$, K^0_S, Λ, ϕ, and Ξ^-, allowing for a comprehensive discussion of strangeness production in this system.

1. INTRODUCTION

The study of hot and dense nuclear matter by means of relativistic nucleus-nucleus collisions is one of the main topics of high energy heavy-ion physics. By these studies one can try to understand the non-perturbative sector of the QCD which is not fully understood up to now. The question is how to relate the specific properties of hadrons like their mass and life time, governed by the non-perturbative QCD on one side, with the quark and gluon composition of the hadrons from the other side. One of the possibilities would be to "place" the hadron into a hot and/or dense matter, which is created in the collision process of heavy ions, and investigate how its vacuum properties in terms of mass and life time are modified. The possible changes of hadron masses and decay widths in such a matter are often discussed in the context of the restoration of the broken chiral symmetry [1]. On the other hand hadronic models also predict significant meson mass changes due to strong meson-hadron couplings, but there is no clear connection between these two scenarios [2].

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QCD sum rules relate only the integrals over the meson spectral functions with the QCD condensates [3]. Moreover, only if the hadron decays inside the created matter, one can hope to see its in-medium modifications. In this context, from the experimental point of view, the most promising hadron to look at is the ρ meson. Because of its short life time ($c\tau \sim$ 1.32 fm) it decays inside the created volume, and the original information about this state can be obtained through its decay products. In a similar way also ω and ϕ mesons can be explored, but due to their longer live times, they decay only partially inside the collision zone. Unfortunately, the preferential hadronic decay channels of these mesons are not well suited for such investigations, because the final products strongly interact with the nuclear matter. Therefore, it is preferable to study electromagnetic decays of the hadrons into lepton pairs, as leptons do not undergo strong final state interactions. However, the finally observed dileptons originate from different sources and phases of the collision process. In general, besides vector meson decays, dileptons are produced through NN bremsstrahlung and Dalitz decays of π^o, η mesons and of baryon resonances. In particular, at low energies (1–2 AGeV) bremsstrahlung and Dalitz decays of baryons are important but poorly known sources and must be determined from *pp* and *np* interactions. Indeed, according to the model calculations NN bremsstrahlung plays an important role for the *np* reaction, while for the *pp* reaction the contribution from the Δ isobar dominates the spectra [4, 5]. This implies the importance of experimental studies of *np* reactions. These sources are in particular important in the first stage of collision. In the further course of the reaction dileptons are emitted from the hot and dense phase of the collision process and finally from the freeze-out part (long lived components) when particles do not interact any longer. The latter is known in a model independent way by hadron (π^0, η) yield measurements from other experiments. In order to reveal the contribution from the hot and dense phase, it is important to subtract the dilepton yield emitted after the freeze-out stage as well as properly take into account the contribution from first-chance elementary reactions.

The DLS collaboration at the Bevalac has formerly reported an enhancement over known hadronic sources in CC and CaCa reactions at 1 AGeV [6]. In contrast to the high energy regime [7, 8], these results could not be explained by theoretical calculations, leaving the question whether the observed enhancement is related to the properties of the created medium or to contributions from elementary collisions which at this stage were not yet known with sufficient precision.

2. DILEPTONS

The High Acceptance Di-Electron Spectrometer (HADES) [9] operates at the Helmholtzzentrum für Schwerionenforschung (GSI) in Darmstadt, Germany. As a result of several experimental campaigns HADES has established the dilepton excess, i.e. the enhancement in the dilepton spectra over the long-lived components coming from the freeze-out phase in CC collisions at 1 and 2 AGeV, as well as in the medium-heavy Ar+KCl system at 1.76 AGeV [10–12]. This is demonstrated in Fig. 1 by comparing CC data at 1 AGeV to the freeze-out components ($\pi^o, \eta \rightarrow e^+e^-\gamma$, $\omega \rightarrow e^+e^-$). Furthermore, the HADES CC data agree with the corresponding DLS measurements remarkably well [10]. Moreover, comparing our CC data taken at two different beam energies, the energy dependance of the excess yield has been established [10]. This comparison reveals that the excess scales with beam energy like pion production. It is well known that at these beam energies pion production is mediated by the Δ resonance [13]. Therefore, it is then suggestive to link the observed excess to the baryon resonance decay and/or NN bremsstrahlung processes during the early stages of the collision (first-chance collisions). To verify this, we have measured *pp* and quasi-free *np* reactions at 1.25 AGeV, i.e just below the η production threshold in *pp*. The quasi-free *np* reactions were selected by triggering on the forward-going spectator proton in *dp* reactions [14].

The comparison of the obtained reference NN spectra (defined as average of the *pp* and the quasi-free *np* data) with the CC data at 1 and 2 AGeV, after subtraction of the η yield (representing a long-lived contribution from the freeze-out) and normalization to the pion multiplicities, is shown in Fig. 2. For the CC case, the η contribution was determined from the measured η multiplicities by the TAPS collaboration [15], whereas for the *np* case it was taken from data on the $pn \rightarrow pn\eta$ and $pn \rightarrow d\eta$ reactions [16]. As it is seen from this figure, in the mass range of $0.15<\mathrm{M[GeV}/c^2]<0.5$ where the excess is defined, both CC data sets are overlapping within experimental errors. This, as was mentioned above, points to a similar energy scaling of the excess and pion yields. Moreover, within 30% (experimental errors), the CC data are described by an incoherent sum of the *np* and *pp* data. This observation indeed underlines the importance of the dilepton contributions from the early stages of the collision process. It is then obvious that, the long standing puzzle of the e^+e^- excess is related to the dilepton emission mechanisms in elementary *pp* and *np* reactions.

As already mentioned above, in the 1–2 AGeV energy regime the dileptons originating from intermediate nucleon lines (known as NN bremsstrahlung) and from Dalitz decays of Δ isobar state (excitation of an intermediate Δ state followed by its decay through $\Delta \rightarrow Ne^+e^-$) are very important pair sources. It is not so trivial to separate these two contributions because of the interference effects between different Feynman diagrams describing this process. However, the contrast between these contributions can be obtained by a simultaneous investigation of the pp and np reactions. Two model calculations, both using the effective Lagrangian approach [4, 5], were performed in order to describe the pp as well as np data measured by HADES. While our pp data is quite reasonably described by [5], both calculations were failing in describing the np data. By including in the model electromagnetic form-factors at the pion and nucleon vertices, the authors of [5] improved substantially the description of np data [17].

Next, in order to investigate the system size dependance of the excess, we have studied dilepton production in the Ar+KCl system. In contrast to the CC case, the normalized Ar+KCl data are no longer described by the NN reference spectrum (see Fig. 3). This result can be interpreted as the onset of contributions from the dense phase of the collision. Indeed, we find that the excess shows a non-linear scaling with the number of participants ($\sim \mathrm{A}_{\mathrm{part}}^{1.4}$), which can be attributed to the importance of multi-step processes in the dense phase of the collision process. Furthermore, around M=0.78 GeV/c^2 a clear ω signal could be reconstructed for the first time at SIS energies in nucleus-nucleus interactions.

3. STRANGENESS

Measurements of the $K^{\pm}$, K^0, Λ, ϕ, and Ξ^- particles have been performed as well by the HADES collaboration in the Ar+KCl collision system [19, 20, 20–22]. The obtained yields, except for $\Sigma^{\pm}$ calculated by using the strangeness conservation, were fitted with a statistical hadronization model [23] as illustrated in Fig. 4. Because the number of charged particles and baryons are much higher compared to the corresponding number of strange particles, the mixed canonical ensemble with exact conservation of strangeness and grand canonical one for the other quantum numbers were used during this fitting procedure. Except for the double strange Ξ^- baryon, we get a reasonable description of all other particles species. Another interesting result obtained in these studies is that the absolute yields of ϕ and Ξ^-

states are similar which is in sharp contradiction to the strangeness suppression mechanism implemented in the statistical models within the canonical ensemble [24]. Moreover the obtained ϕ/K^- ratio shows that $\approx 18\%$ of all produced K^- mesons are originating from the ϕ decay. It was demonstrated in [25], that the difference in inverse slope parameters for different kaon species can be explained to a large extent by taking into account this important source for the K^- production.

4. CONCLUSION

We reported on dilepton, as well as, strangeness production studies performed by the HADES collaboration in different collision systems. It was established that the inability of transport models to describe the old DLS data is connected to an insufficient treatment of radiation coming from the early stages of the collision process, which can be traced back to the elementary np reaction channel. Furthermore, in the medium-heavy Ar+KCl system the intermediate-mass yield was found to be even more enhanced, indicating that contributions from the dense phase of the collision set in. A measurement of open and hidden strangeness states were performed in the Ar+KCl collision system. A statistical model fit was applied to the measured hadron yields, showing large discrepancy for the Ξ^- state. Moreover the observed similar yields of strangeness neutral ϕ and double strange Ξ^- particles contradict the additional strangeness suppression mechanism used in statistical models within the canonical ensemble.

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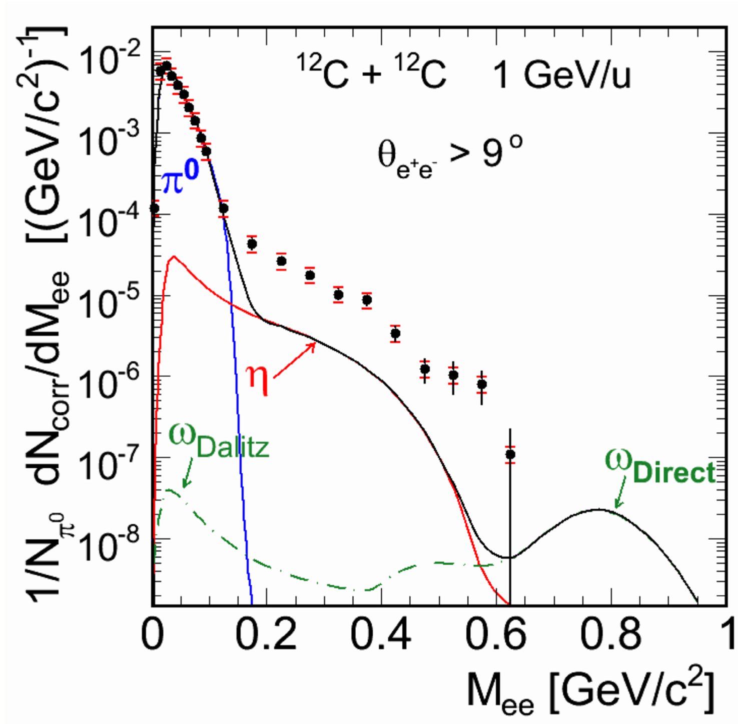

Figure 1. Efficiency corrected and background subtracted invariant mass distribution of e^+e^- pairs (full circles), compared to the thermal dilepton cocktail of long-lived components (π^0, η, ω). A clear enhancement over the long-lived components in the intermediate mass region is observed.

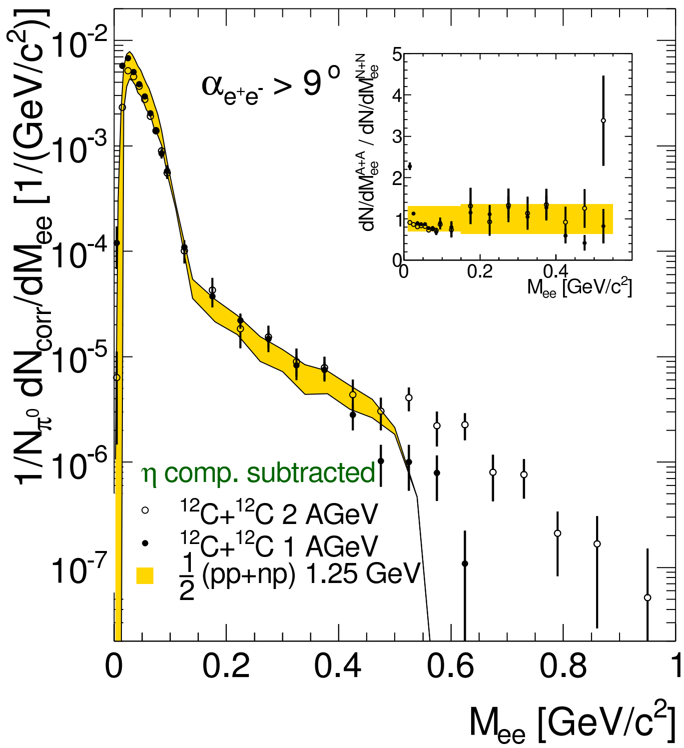

Figure 2. Comparison of the reference spectrum (defined as the average of *pp* and *np* data at 1.25 AGeV) with the CC data at 1 (full circles) and 2 AGeV(open circles). All spectra are normalized to respective pion multiplicities. From CC and *np* data the corresponding η components are subtracted. In the inset the ratio to the reference spectrum in the excess range is shown.

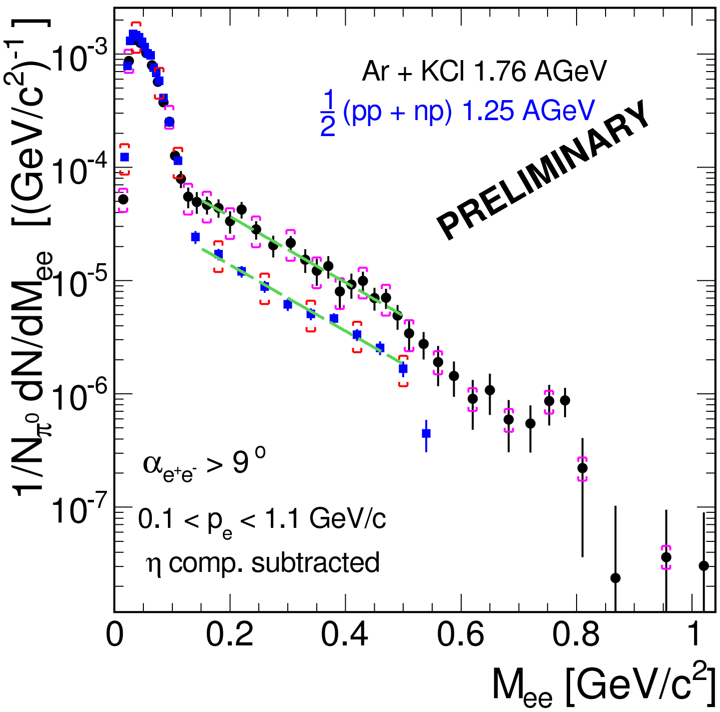

Figure 3. Comparison of the reference spectrum (defined as the average of *pp* and *np* data at 1.25 AGeV) with the Ar+KCl data at 1.76 AGeV. All spectra are normalized to their respective pion multiplicity. From Ar+KCl and *np* data the corresponding η components are subtracted.

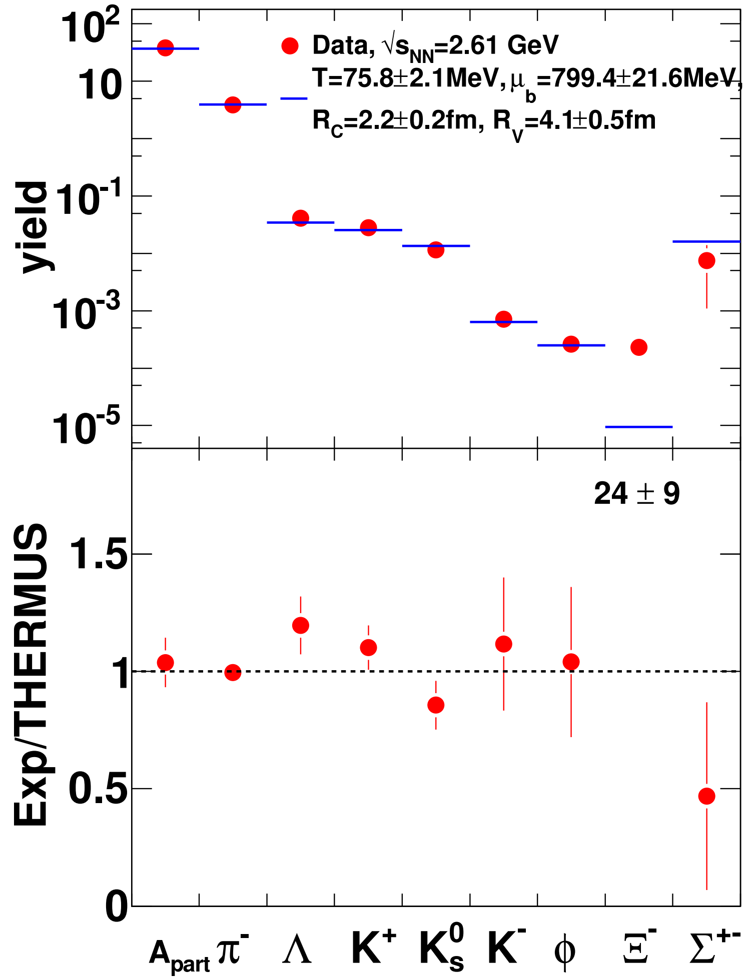

Figure 4. Upper part: Hadrons yields reconstructed in Ar+KCl reactions (red circles) and the corresponding THERMUS fit results (blue bars). Lower part: The ratio of the experimental yields and the fit results. The ratio for the Ξ^- is quoted as a number.

FIGURE CAPTIONS

Fig.1: Efficiency corrected and background subtracted invariant mass distribution of e^+e^- pairs (full circles), compared to the thermal dilepton cocktail of long-lived components (π^0, η, ω). A clear enhancement over the long-lived components in the intermediate mass region is observed.

Fig.2: Comparison of the reference spectrum (defined as the average of pp and np data at 1.25 AGeV) with the CC data at 1 (full circles) and 2 AGeV(open circles). All spectra are normalized to respective pion multiplicities. From CC and np data the corresponding η components are subtracted. In the inset the ratio to the reference spectrum in the excess range is shown.

Fig.3: Comparison of the reference spectrum (defined as the average of pp and np data at 1.25 AGeV) with the Ar+KCl data at 1.76 AGeV. All spectra are normalized to their respective pion multiplicity. From Ar+KCl and np data the corresponding η components are subtracted.

Fig.4: Upper part: Hadrons yields reconstructed in Ar+KCl reactions (red circles) and the corresponding THERMUS fit results (blue bars). Lower part: The ratio of the experimental yields and the fit results. The ratio for the Ξ^- is quoted as a number.