Recent results on dilepton and strangeness production with HADES

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Abstract.
Selected topics of the HADES research program are discussed with an emphasis on the results obtained by studying proton-proton and proton-niobium collisions at a beam energy of 3.5 GeV. Future directions of the measurements at HADES are outlined.

1. Introduction
HADES is a versatile detector located at GSI Helmholtzzentrum für Schwerionenforschung and currently operating at the SIS18 accelerator in the range of beam energies of 1-2 GeV/u (for nucleus-nucleus collisions), up to 3.5 GeV in proton-induced reactions. A short description of the experimental setup is given in the contribution [1] to these proceedings and a detailed review can be found in [2]. The ultimate goal of the HADES searches is to reveal signals of hadron modification expected to occur at finite net baryonic densities as a manifestation of a partial restoration of the spontaneously broken chiral symmetry. In this respect, primary objects of interest are light unflavoured vector mesons ($\rho$, $\omega$, $\phi$), accessible via di-electron measurements, and (anti)kaons. The strategy is to perform systematical measurements ranging from elementary nucleon-nucleon reactions to collisions of heavy nuclei.

In the following we concentrate mostly on the measurements performed in proton-proton and proton-niobium collisions at a beam kinetic energy of 3.5 GeV. For the results on dilepton and strangeness production in light (C+C) and medium-size (Ar+KCl) systems we refer to [3] and references therein.

2. Measurements in p+p and p+nb reactions
Studies of dilepton and strangeness production in proton-proton collisions at a beam energy of 3.5 GeV set a reference for the interpretation of the data obtained in proton-niobium collisions at the same energy. The nucleus acts here as a well controlled strongly interacting environment with a known density profile, so the possible in-medium effects at saturation density might be probed.

2.1. Vector mesons: $\omega \rightarrow e^+e^-$
A measurement of the electron-positron pair production in proton-proton collisions at a beam kinetic energy of 3.5 GeV was performed by the HADES collaboration [4]. Fig. 1 shows the invariant mass spectrum of signal $e^+e^-$-pairs together with a “cocktail” of individual...
contributions simulated with the PYTHIA and Pluto event generators (employed for the treatment of the production and decay processes, respectively). The low-mass region $M_{ee} < 0.15$ GeV/c$^2$ is saturated by the Dalitz-decays of the $\pi^0$-meson; the intermediate mass range $0.15 < M_{ee} < 0.5$ GeV/c$^2$ is dominated by the Dalitz-decays of the $\eta$-meson with certain contributions of the channels $\Delta \to N e^+ e^-$ and $\omega \to \pi^0 e^+ e^-$. Finally, a distinct peak corresponding to the direct decays of the $\omega$-meson on top of the broad $\rho$-meson contribution is visible. The description of the experimental data with the PYTHIA cocktail is not satisfactory: there is a large gap below the $\omega$ pole.

Figure 1. Invariant mass spectra of electron-positron pairs measured in p+p (open circles) and p+ Nb (full circles) collisions. For the p+p measurement a dilepton cocktail simulated with PYTHIA is shown.

Figure 2. Comparison of the invariant mass spectra measured in p+p and p+ Nb reactions for slow electron-positron pairs ($P_{ee} < 0.8$ GeV/c).

A possible remedy for this discrepancy is discussed in [5]. Here a contribution of a number of $N^*$ and $\Delta^*$ resonances to the final $e^+ e^-$-pair spectrum is included. A strict vector meson dominance model is considered, forcing all electromagnetic transitions to proceed via an intermediate $\rho$-meson: $N^* \to N \rho \to N e^+ e^-$ and introducing thus a duality between the contribution of the baryonic resonances and the contribution of the off-shell $\rho$-meson. Within this approach, the missing yield in the invariant mass spectrum below the $\omega$-pole is effectively filled by the contribution of the baryonic resonances. Whereas the specific shares of individual contributions are not known precisely, this interpretation strongly points to the importance of the resonances’ contribution in this energy range.

The invariant mass spectrum of pairs reconstructed in proton-niobium collisions [6] is shown on Fig. 1 as well. A comparison to the reference measurement in proton-proton collisions has been made for slow electron-positron pairs ($P_{ee} < 0.8$ GeV/c) in the vicinity of the $\omega$-peak (Fig. 2). To facilitate the comparison, the p+p spectrum has been scaled up according to a Glauber model, see [6] for details. The observed excess located left to the $\omega$-peak might be interpreted as a contribution from baryonic resonances formed in secondary processes, such as $\pi N$-reactions. Since these resonances strongly couple, as discussed above, to the off-shell $\rho$-meson, the presented data contains information about the in-medium $\rho$-meson spectral function.
2.2. Neutral kaons: $K^0_S \to \pi^+\pi^-$
Analysis of the inclusive $K^0$ production in proton-proton collisions (preliminary results of which were reported in [7]) yields important constraints for the models describing the production of strangeness in proton-nucleus and nucleus-nucleus reactions. Comparison of the data with a resonance model of kaon production [8] showed that the model gives unsatisfactory description, overestimating the total production cross section and failing to describe the shape of transverse momentum spectra. This disagreement is not surprising, since it is known that this model strongly overestimates the production cross section in a number of channels, such as for example $pp \to p\pi^+\Lambda K^0$ [9].

Analysis of the inclusive neutral kaon production has been continued in p+Nb collisions with a goal to probe the sensitivity of the kaon spectra to the in-medium interaction of kaons in terms of the repulsive in-medium potential. Interpretation of the data with a help of the GiBUU transport model [10], which allows to simulate the propagation of kaons in a mean-field potential generated by the baryonic density, is in its final stage. Model calculations show that the experimental data are sensitive to the effect of the repulsive potential.

Figure 3 shows the region of the $K^0$ rapidities experimentally accessible in p+nb reactions.

![Figure 3. $K^0_S$ rapidity distribution in p+nb collisions represented in the nucleon-nucleon center-of-mass reference frame.](image)

2.2.1. $\Lambda(1405)$ The strange baryons $\Sigma(1385)$ and $\Lambda(1405)$ were reconstructed at HADES in proton-proton collisions ([11] and [12], respectively). The $\Lambda(1405)$ enjoys particular theoretical attention due to its key role in the understanding of the low-energy antikaon-nucleon interaction. The presence of the $\Lambda(1405)$ just below the $KN$ threshold makes the problem of the antikaon-nucleon interaction complex and requires a treatment within a coupled channel approach. Within this approach the $\Lambda(1405)$ is understood as a dynamically generated state with two main contributions: an antikaon-nucleon bound state and a $\Sigma\pi$ resonance.

The reaction $p+p \to p+\Lambda(1405)+K^+$ was analysed and the missing mass spectrum $MM(p,K^+)$, showing a signal of the $\Lambda(1405)$ (the gray band) is presented on Fig. 4. Most interesting is the location of the $\Lambda(1405)$ mass peak — well below 1405 MeV/c$^2$. This is a first reconstruction of the $\Lambda(1405)$ in proton-proton collisions in the charged decay mode and these data give a new input to models describing the production of $\Lambda(1405)$.

Since an antikaon-nucleon bound state is realised in nature as a contribution to $\Lambda(1405)$, one might ask whether a system of two nucleons bound by an antikaon, a $ppK^-$ state, might exist. Indeed, a hypothesis of an existence of such a system has been put forward in [13, 14].
Figure 4. Sum of missing mass $MM(p, K^+)$ distributions reconstructed with the $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ pairs. The gray band shows the contribution of the $\Lambda(1405)$. Solid gray curve corresponds to the incoherent sum of all relevant channels (see the legend).

The HADES collaboration is currently performing a search for the simplest kaonic cluster in a reaction $pp \rightarrow pK^+\Lambda$, more details can be found in [15].

3. Outlook

After a profound upgrade of the experimental apparatus, the HADES detector successfully measured collisions of heavy ions Au+Au at a beam energy of 1.23 GeV/u. A discussion of the dilepton measurement can be found in a dedicated contribution to these proceedings [16].

A number of strange hadrons (charged kaons and antikaons, $K^0_S$, $\Lambda$ and $\phi$), all produced sub-threshold with respect to free nucleon-nucleon reactions, were reconstructed. A novelty in this experimental campaign was the possibility to reconstruct the reaction plane looking at the spectator protons and light fragments with a dedicated Forward Wall hodoscope, which covers low polar angles. This allows to analyse the anisotropy of the particle emission relative to the reaction plane on the event-by-event basis, which is sensitive to the in-medium interaction of various hadron species with the bulk nuclear matter.

An experiment with a pion beam offers a natural continuation of the HADES measurements of dilepton and strangeness production in proton-proton and proton-nucleus collisions. The usage of a light projectile allows to produce hadrons with low momenta in the target reference frame, ensuring optimal conditions for the observation of the in-medium effects. Of particular interest is to measure production off several nuclear targets (light and heavy) with an aim to perform a comparative analysis.

In future, HADES will continue to explore dense baryonic matter at the FAIR facility and perform measurements at beam energies of up to 8 GeV/u provided by the SIS100 heavy-ion synchrotron. This energy region lies above the vector meson production threshold and has not been yet explored by means of dilepton spectroscopy. The HADES detector will be installed in a common cave with the CBM experiment and the latter will continue measurements at even higher energies. The fitness of the experimental apparatus for the demanding conditions of a high charged-particle occupancy has been already checked with a recent measurement of Au+Au collisions.

Transition to higher beam energies will open a possibility to probe baryonic densities comparable to those achieved in the interior of the neutron stars. Of special interest in this
respect is the study of multistrange baryons ($\Xi^-$, $\Omega^-$) and hypernuclei. They serve as a probe of the hyperon interaction at high baryonic densities — a topic relevant for the question of the strangeness appearance in the interior of neutron stars [17].

4. Conclusions
As discussed in the present contribution, study of elementary nucleon-nucleon reactions delivers a basis for the interpretation of proton-nucleus and nucleus-nucleus collisions. Besides, already the vacuum properties of certain particles such as the $\rho$-meson (due to its strong coupling to baryonic resonances) or the $\Lambda(1405)$ baryon (due to its complex, molecular-like nature) are of interest by themselves.

Proton-nucleus reactions offer a next level of complexity. Here, the in-medium behaviour of various meson species propagating inside a nucleus, including $\omega$-mesons and neutral kaons, was studied by HADES. A truly heavy colliding system (Au+Au collisions at 1.23 GeV/u) was measured by HADES in 2012 and a number of analyses is on-going with first promising results both in the dilepton and in the strangeness sector.

In the near future, HADES has a unique opportunity to perform measurements with pion-induced reactions characterized by favourable conditions for an observation of in-medium effects. After completion of the experimental program at SIS18, HADES will move to FAIR and will continue measurements at SIS100 at beam energies of up to 8 GeV/u.

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