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In-medium hadron properties measured with the HADES

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The High Acceptance DiElectron Spectrometer HADES is installed at the Helmholtzzentrum Für Schwerionenforschung (GSI) accelerator facility in Darmstadt (Germany). It investigates dielectron emission and strangeness production in the 1-3A GeV regime. In this energy regime HADES has measured hadrons and dielectron signals in C+C, Ar+KCl, p+p, d+p and p+Nb collisions. For the first time, e^+e^- pairs were reconstructed from quasi-free n+p sub-reactions by detecting the proton spectator from the deuteron breakup. Also for the first time dielectrons radiated from cold nuclear matter in a kinematic regime (low momenta) where strong medium effects are expected have been detected. In contrast to other experiments, the high acceptance of the HADES allows for a detailed analysis of electron pairs with low momenta relative to nuclear matter where modifications of the spectral functions of the vector mesons are predicted to be most prominent. An experimentally constrained N+N(nucleon-nucleon collision) reference spectrum was established. A direct comparison of the latter with the e^+e^- invariant mass distribution measured in the heavier system Ar+KCl at 1.76 AGeV shows an excess yield above the reference. This observation can be interpreted as the onset of an actual medium effect.

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1. Introduction

The relation between chiral symmetry restoration and hadron properties inside a strongly interacting medium is a much debated topic and has motivated plenty of work, both in theoretical and experimental physics. Sizable spectral modifications have been predicted by various theoretical models for hadrons embedded into cold or hot and dense nuclear matter. In this respect, most attention has been focused on properties of the light vector mesons (ρ and ω) as probes of chiral symmetry restoration (for reviews see [1, 2]). Early work based on QCD sum rules suggested a direct link between changes of the meson masses and QCD vacuum properties, characterized by a reduction of the expectation value of the two-quark condensate [3, 4]. More recent work shows however that, while such a link indeed exists, it is much more sophisticated than originally thought [1]. A consistent picture of in-medium hadron properties has however not yet emerged, asking for more experimental input and yielding the question to what extent a relation between observed hadron masses and chiral symmetry restoration is possible.

On the experimental side, a lot of activities have been carried out over the last years investigating light vector meson production on nuclei with proton and photon beams, as well as in heavy ion reactions. Two experimental approaches have been used to measure in-medium modifications of the vector mesons: (i) directly via the reconstruction of their invariant mass distribution from the detected decay products and (ii) by quantifying the meson absorption in nuclei from their production yields and by connecting these to the in-medium width Γ_{tot} via model calculations (this method is used for p(γ)+A collisions). The density and temperature reached in Heavy Ion (HI) collisions is of course higher and larger effects can be expected but one has to properly model the time evolution of the collision system to calculate dilepton radiation. Moreover, in order to access the true in-medium radiation one has to subtract the contribution of mesons decaying in the late state of the HI collision, that is after the so called "freeze-out" where all interactions between the produced particles have ceased.

Results from p(γ) + A experiments have not yet produced a consistent picture: while the E325 experiment at KEK claims [5] the observation of a mass drop of the ρ meson in the e^+e^- invariant mass spectrum according to the Brown-Rho scaling [4], investigations at JLab (CLAS) [6, 7] does not corroborate such a conclusion showing only a slight broadening of the ρ. Transparency measurements for the ω at ELSA/MAMI (CBELSA-TAPS) [8] and JLab [6, 7], and ϕ at COSY (ANKE) [9], LEPS at SPring-8 [10] indicate large absorption of both mesons. However, the extraction of the in-medium widths from the measured nuclear transparency is not straightforward and remains model dependent. In heavy-ion collisions, the search for vector meson mass modifications via dilepton spectroscopy was pioneered by the CERES [11] and HELIOS/3 [12] collaborations at the CERN SPS and the DLS experiment [13] at the Bevalac. Below the ρ/ω pole, a low-mass pair excess, above the yield expected from free hadron decays after freeze-out, was reported and was widely discussed in many theoretical papers (for a review see [2]). Though the limited statistics of these experiments did not allow to derive final conclusions, results obtained at SPS indicate that the excess is related to pions annihilating into the ρ meson, and is hance directly linked to the ρ in-medium spectral function. The breakthrough in this field was achieved with the high-statistics NA60 data set at 158 AGeV which allowed, for the first time, to extract the in-medium spectral function of the ρ meson [14]. Comparisons to various theoretical calculations show that the spectral function is mainly affected by two in-medium effects: (i) modification of the pion loop in the ρ meson self-energy and (ii) direct rho-meson couplings to low-mass baryon resonance-hole excitations [15]. Furthermore, it appears that the second mechanism plays the essential role in the observed melting of the ρ meson in hot and dense nuclear matter. On the other hand, the mass dropping scenario was found to be not supported by the data. Results of the DLS experiment [13] (the energy scale at 1-2 AGeV), could not find a satisfactory explanation for a long time. Dielectron spectra measured even in light C + C collision were not described by any model calculation showing a large excess in the mass 0.15<$M_{e^+e^-}$ <0.6 GeV/c^2 range. However, nuclear matter probed in this energy range is dominated by baryons (nucleons and up to 30% low mass-baryonic resonances) and it has a different composition from the meson (mainly pion) dominated matter probed at the SPS. Therefore, it remained unclear if the DLS excess is due to some particular features of baryonic sources not properly modeled in the calculations or is a signature of true in-medium effects.

2. The HADES experiment

The experimental challenge in di-electron measurements is to discriminate the penetrating but very rare leptons from the huge hadronic background, which typically exceeds the electron signal by orders of magnitude. The HADES detector [17] has been specifically designed to overcome these difficulties. This unique apparatus is installed at SIS18 at the GSI Helmholtzzentrum für Schwerionenforschung (Germany) to study electron pair (e^+e^-) and hadron production in heavy-ion, as well as in elementary reactions in the energy regime of 1-3A GeV. The achieved mass resolution of $\sigma(M^{\omega}_{pole})$ = 16 MeV/c^2 provides high sensitivity to possible changes of the in-medium spectral function of vector mesons. By now HADES has measured di-electrons in C+C, Ar+KCl, p+p, d+p and p+Nb collisions. Measurements in p+p collisions at various beam energies (1.25, 2.2, 3.5A GeV) and d+p (at 1.25A GeV) provide valuable constraints on the various di-electron sources. They allowed to establish model independent reference spectra for studies of cold nuclear matter in p+A collisions and hot and dense matter in A+A collisions.

3. Results from p+A collisions

p+p and p+Nb collisions at a beam energy of 3.5 GeV have been studied by HADES with the main goal to search for in-medium modifications of the vector mesons in cold nuclear matter [21, 20]. The large acceptance of the detector and the rather low energy of the beam allow for the first time to detect e^+e^- pairs down to low momenta ($P_{e^+e^-}$ < 1GeV/c) not possible in the CLAS and E325 experiments.

Differential e^+e^- production cross sections as a function of the e^+e^- invariant mass (Fig. 2 (a)), the momentum and the rapidity have been measured for both reactions [20]. The direct comparison of the measured distributions to the yields expected from the known hadronic sources (from a PYTHIA calculation) is shown for p + p collisions in Fig. 2 (a) [21]. The strength below the vector meson pole mass can not be accounted for by such a cocktail. The situation is even more dramatic in p+Nb collisions.

Indeed increase of the e^+e^- yield below the ω vector meson pole above the p + p reference is visible for low momenta $P_{e^+e^-}$ < 0.8 GeV/c. At the same time, the e^+e^- yields in the ω pole for the same e^+e^- momenum selection are the same. This might be interpreted as a fingerprint of the contribution of secondary processes of the type p+p $\rightarrow \pi$ X, π N $\rightarrow$ R $\rightarrow$ Ne^+e^- adding also to this mass region because of the aforementioned strong resonance-ρ couplings. On the other hand, most of model calculations based on hadronic many-body interactions predict that such couplings strongly modify the in-medium ρ meson spectral function. Therefore, final conclusions about in medium modifications of the ρ meson in cold nuclear matter can be derived only if a consistent treatment of the spectral shape of the ρ in the medium together with a correct handling of the additional yield from secondary reactions is achieved.

As far as the ω meson in concerned, we observe that, for slow pairs, the yield at the ω pole is not reduced, however, for the underlying smooth distribution in enhanced. This indicates a strong ω absorption in contrast to the pairs from the underlying continuum. Furthermore, analysis of the ω width shows, within the error bars, no significant broadening. Both observations are in line with the results of the CBELSA-TAPS experiment [8].

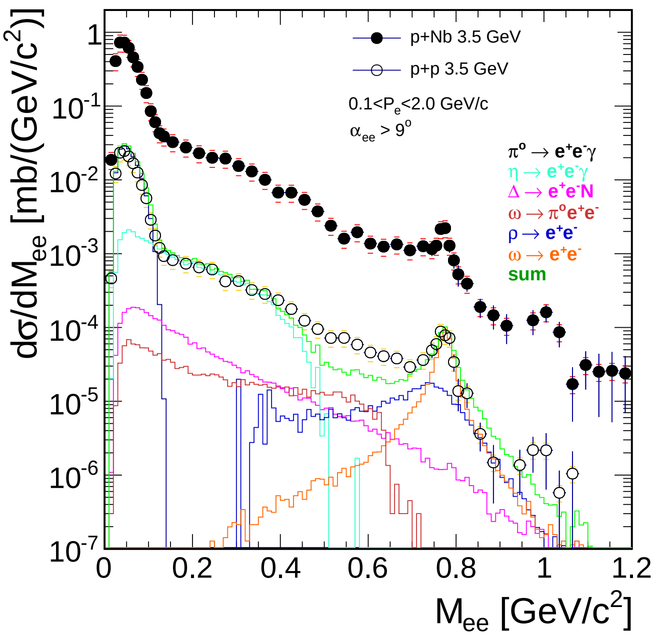

Figure 1: Comparison of dielectron cross-sections as a function of the invariant mass measured in p+p and p+Nb collisions in full momenta range.

4. Results from A+A collisions

In order to search for a true in-medium radiation off the dense nuclear phase of HI collisions we compare e^+e^- production rates found in nucleus-nucleus (C+C [24], Ar+KCl [22]) reactions with a superposition of the production rates measured in elementary collisions (n+p, p+p [19]). Figure 2 (left-handside) shows the ratio of the pair multiplicities measured in nucleus-nucleus collisions to the averaged $1/2(M_{pp}^{e^+e^-} + M_{pn}^{e^+e^-})/M_{\pi^0}$ obtained from the e^+e^- cross-section. For this kind of comparison, the respective η Dalitz contributions have been subtracted from all distributions. This is motivated by a very different excitation function of the η meson production in nucleus-nucleus

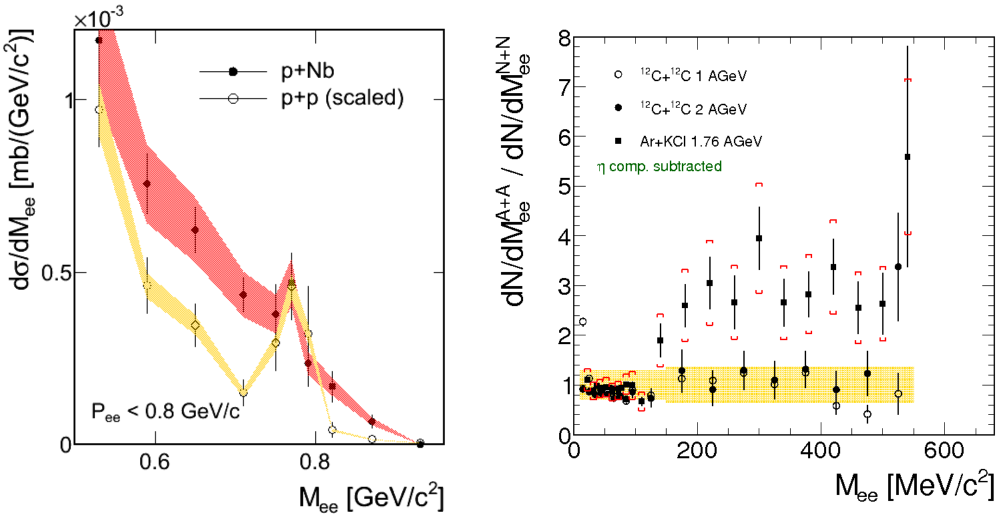

Figure 2: Comparison of dielectron cross-sections as a function of the invariant mass measured in p+p and p+Nb collisions for the low momenta pairs (a). (b) ratio of e^+e^- invariant mass distributions measured in Ar+KCl and C+C with subtracted η meson contribution to the N+N reference spectrum.

and N+N reactions and facilities comparison of collision systems measured at different beam energies. In case of C+C collision (at 1 and 2 AGeV kinetic energies) the ratio is consistent, within the statistical and systematical uncertainties (of about 25%) with the reference. This result suggests that radiation out of a medium is not observed in this light collision system. This observation is also conected to the long standing "DLS puzzle" of the unexplained yield measured in C + C collisions. In this context we shall emphasize that the DLS and HADES data agree within errors bars as shown by our dedicated analysis [25, 26]. However a significant excess (2.5-3) with respect to the N+N reference is visible for the Ar+KCl system above the π^0 mass (see Fig.2 (c)). This calls for an additional contribution from the dense phase of the heavy ion collision. This observation can be interpreted as a signature of the onset of a contribution of multi-body and multi-step processes in the hot and dense phase created in collisions of nuclei of sufficiently large size. In this context, the propagation of short-lived baryonic resonances seems to play a main role. A further important test will be provided by the data obtained from Au+Au collisions at 1.25A GeV in the year 2012.

5. Conclusion and Summary

HADES provides high-quality data for the understanding of di-electron production in elementary and heavy-ion collisions at SIS energies. The HADES results demonstrate that electron pair emission in C+C collisions can essentially be explained as a superposition of independent N+N collisions. Our results on e^+e^- production in Ar+KCl collisions, however, show a strong enhancement of dilepton yield relative to a reference spectrum obtained from elementary N+N reactions. Moreover, for the first time at SIS energy, a clear omega signal was observed. This result allows putting tight constraints on vectors meson production in heavy-ion collisions at few GeV per nucleon beam energies. On the other hand according to hadronic models medium modifications are expected to be most pronounced for particles with small relative momenta to the surrounding medium a region which is challenging to access in experiment. Recently HADES has published data on inclusive e^+e^- pair production in p+Nb reactions at beam kinetic energy of 3.5 GeV, representing the first high statistics measurement with small e^+e^- pair momenta relative to the medium. These results are compared to reference data measured in p+p reactions at the same incident beam energy in order to extract medium modifications.

The HADES physics program will be continued towards larger collision systems and to higher beam energies, where the baryon densities are substantially higher and the in-medium effects are expected to be more pronounced.

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