HADRONS IN MEDIUM – OBSERVABLES

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Abstract

The observable consequences of a lowering of the restmasses of vector mesons on dilepton spectra in the SIS energy regime (HADES) and on photoabsorption cross sections on nuclei are studied in a transport-theoretical framework. We also investigate the consequences of a mass-shift of kaons in dense matter and compare with recent SIS data. The need for a detailed understanding of the elementary processes is underlined.

1 Introduction

Predictions of marked changes of hadronic properties in medium have recently found widespread interest because these predictions are usually based on some approximation to QCD. Directly QCD-related effects, such as the predicted partial restoration of chiral symmetry at high nuclear densities, might thus be observable in dense nuclear systems \[1, 2\]. The overall picture, though, is somewhat confusing since more ‘classical’ mechanisms, such as meson-baryon couplings also lead to changes of mesonic properties in the medium \[3, 4\]. In addition, all these calculations are based on highly idealized scenarios in which infinite nuclear matter at high density rests forever in an equilibrium state. This assumption is, of course, never realized in a nuclear reaction, the less so the more violent the collision is.

We have, therefore, now for several years developed semiclassical transport theories that allow one to follow the dynamic evolution of a nuclear reaction, be it between two heavy ions or between a hadron or photon and a nucleus. In this way we can keep track of the dynamical evolution of density and temperature during the collision and can time-locally use the appropriate hadronic properties for the prediction of observables.

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2 Dileptons

The results reported here are based on a newly developed transport code that explicitly propagates all baryonic resonances up to a mass of 2 GeV and in addition the $\pi, \eta, \rho$ and the $\sigma$, the latter being a correlated $2\pi$ pair in an $s$-state $^2$. It contains momentum-dependent self-energies for the baryons, none for the mesons and all resonance decay properties are taken from the particle data booklet.

The CERES data $^6$ clearly show a large surplus in the invariant mass spectrum when compared to so-called ‘cocktail plots’ that are generated from known decays of produced mesons in nucleon-nucleon collisions $^6$. Note, that a very similar effect was already observed by the DLS group working at the BEVALAC in Berkeley $^7$; there the $\eta$- and the $\pi$-Dalitz decays could not explain the dilepton spectra in the high-mass region. This deficiency was explained by us as being due to secondary reactions in which the produced pions collide to form a $\Delta$ which then decays again $^8, ^9, ^10$. If this same effect is taken into account in analyzing the CERES data the dramatic discrepancy of a factor 5-7 is reduced to about a factor 3, but – contrary to the DLS case – does not disappear. Dynamical simulations have shown that this surplus can indeed be explained if the mass of the $\rho$-mesons is decreased according to the QCD sum rule prediction $^{11}$.

We have recently shown that at bombarding energies of about 1 - 2 A GeV the dilepton spectrum contains all the same components as in the CERES experiment at a much higher energy regime $^{12}$. The relative weights are, of course, somewhat different and the nucleon-nucleon bremsstrahlung, which proceeds mainly through an excitation of an intermediate $\Delta$ $^{13}$, plays an important role at the lower bombarding energy for invariant masses below about 400 MeV. It is thus essential to know this component reliably and we have, therefore, recently done microscopic calculations of this process employing a realistic $T$-matrix that describes the NN scattering phases up to about 1 GeV $^{13}$.

The full dilepton spectrum calculated with the new transport code, both without and with a medium-dependent shift of the $\rho$-meson mass is shown in fig. 2. The in-medium shift of the $\rho$ peak leads to a distinct change of the spectrum by a factor of 3, which should be measurable by HADES, the new dilepton spectrometer presently being built for SIS.
Figure 1: Invariant mass spectrum for dileptons for $\text{Au}+\text{Au}$ at 1 AGeV. Shown are the major components, assuming free (left) and medium-dependent (right) masses for the vector mesons. The calculations were performed with the method described in [5], the $\omega$ was not medium-changed.
3 Photoabsorption

An in-medium effect in a completely different type of reaction has recently generated a lot of interest in the photonuclear community. In photoabsorption measurements on nuclei it was found that the higher-lying nucleon-resonances (above the $\Delta$), which are clearly seen in photoabsorption on the nucleon, disappear when the same experiment is performed on a nucleus. This is quite surprising since the photoabsorption cross section on nuclei scales nearly linearly with massnumber $A$.

When explaining these data in terms of Breit-Wigner parametrizations for the individual resonance strengths one is lead to much larger resonance widths than those found for the nucleon \[14, 15\]. In addition, also the overall strength changes somewhat, evidence for shadowing, on the other hand, sets in only at the highest photon energies \[15\].

We have recently calculated the collisional broadening of the resonances by using the same transport theory as developed for the description of heavy-ion resonances \[14\] (see fig. 2). In these studies it turned out that overall the collisional broadening is not very effective and clearly not large enough to explain the complete disapppearance of the resonances (see fig. 3). It also turned out from these studies that the absence of resonances beyond masses of about 1600 MeV could be easily understood in terms of simple Doppler-broadening due to the Fermi-motion which is the more effective the higher the mass of the resonance is. The real challenge then is to understand the absence of the $N(1520)$ $D_{13}$ resonance which in the calculation got somewhat broader, but did not disappear \[14\].

Closer analysis of these results showed, however, that the calculated ‘resonance’ in the photoabsorption channel coincides with the opening of the $2\pi$ background production channel. The latter is misunderstood, even on the nucleon: here the $2\pi$ decay branches of the resonances as given in the particle data booklet can account only for a small part of the observed ($\gamma, 2\pi$) cross section \[14\]. The remainder is then simply ascribed to a background of unknown origin. If this background undergoes an in-medium change such that the $2\pi$ background opens up more slowly, then the ‘resonance’ strength in this region would get diluted.

A further, speculative, effect is based on the same in-medium mass change for the $\rho$ meson as used earlier in calculating the dilepton spectra. The $N(1520)$ resonance has a 20% ($N\rho$) decay branch. Because of the widths of both the resonance and the meson this is possible, even though the resonance lies about 130 MeV below the energetic threshold as calculated from the pole
Figure 2: Total photoabsorption cross section. The dots in the upper part give the data while the lines represent the results of the calculations (for details see [14]). The lower part gives a breakdown of the theoretical cross section into various components.
masses. If now the $\rho$ meson is lowered in the nuclear medium by about 18%, as predicted by the sum rule predictions [1], then the aforementioned decay branch would be energetically open and this would increase the total resonance width dramatically, as can be seen from fig. 3.

4 Kaon Selfenergies

Based on an early suggestion of Nelson and Kaplan [18], the in-medium self-energy of kaons has recently been reinvestigated [19]. In these studies it is found that the restmass of positively charged kaons ($K^+$) increases slightly with density, while that of negatively charged antikaons ($K^-$) is predicted to be lowered significantly. An experimental indication for such an effect seemed to be present in data of the KAOS collaboration at SIS [20] taken at 2 different bombarding energies chosen such that they corresponded to the same energy above the elementary production threshold. These data show that the $K^-$ production cross sections in heavy-ion collisions are as large as those for $K^+$ production. In the absence of any in-medium effects this was unexpected since $K^-$ mesons have a much smaller mean-free-path in nuclear matter than $K^+$ mesons so that the production of the former should be surpressed.
First calculations by Ko et al. [21] have shown that a $K^-$ self-energy indeed has an influence on the production rates. The relative importance of the various microscopic production channels contributing to the observed yield depends very much on the microscopic cross-sections used for the elementary baryon-baryon channel. All the earlier calculations of heavy-ion induced $K$ production used extrapolations of these cross-sections from the few measured points several 100 MeV above threshold down to threshold, since in the most important region around about 200 MeV above threshold no elementary production data are available.

Recently, Sibirtsev et al. [22] have proposed a new model for the microscopic $K^+$ and $K^-$ cross sections that is based on an effective boson exchange model and has the advantage that the cross sections in the various isospin channels are constrained by $SU(2)$ symmetry. In addition, the model automatically includes the correct 4-body to 3-body phase-space factor for $K^-$ vs. $K^+$ production; this was not the case in the earlier parametrizations. Very close to threshold (2 MeV above) the Sibirtsev prediction has found some support recently from the new COSY-11 measurement; it also describes the older data at higher energy [23]. Using these microscopic cross-sections we have recently reanalyzed the kaon production by performing calculations in a transport model, that includes all the relevant kaon-channels [23]. The result of these studies is that the $K^+$ channel is quite well described without using any selfenergy, though a small positive shift cannot be excluded. The $K^-$ production rates calculated without in-medium mass change, on the other hand, lie all below the measured data (see fig. 4). It is interesting to see that the dominant production channel is now the $\pi\Sigma$ entrance channel, i.e. a channel that involves 2 secondary particles, and not the $\Delta - N$ channel as in earlier studies. This is due to the fact that the new cross-sections in the baryon-baryon channel are in the relevant energy range of about 100 - 400 MeV above the elementary threshold lower than the previously used empirical parametrizations. However, when including a lowering of the $K^-$ mass by an amount as predicted by the calculations cited [2] then the cross sections can be reproduced very satisfactorily (see fig. 4).

5 Summary and Conclusions

In this talk I have shown that dilepton spectra in the HADES energy range between about 1 and 2 GeV are composed of the same elementary sources as in the relativistic CERES regime. This observation raises the expectation that both experiments can complement each other; while the latter (CERES) reaches higher densities it also leads to higher temperatures, the former ex-
Figure 4: $K^-$ production cross sections for $\text{Ni} + \text{Ni}$ at the energies indicated. On the left, the solid line gives the sum of all production channels, the line labeled $\pi\pi$ the contribution from pion-hyperon collisions and the curve labeled $Z\&S$ the total cross section when the old parameterization for the baryon-baryon channel is used. On the right, the solid line gives the sum of all production channels, the line containing both reabsorption and mass-reduction of the $K^-$ (from [23]).
periment (HADES) works in a ‘colder‘ environment. The effects of predicted in-medium mass-shifts on the dilepton spectra in the HADES energy range are expected to be as large as in the CERES regime.

I have also pointed out an interesting possible connection of this physics problem with the observed disappearance of nucleon resonances in the photoabsorption cross sections. Here the N(1520) resonance plays an important role: if the $\rho$ meson mass really drops in nuclear matter then already at normal nuclear density the decay width of the resonance into the $N\rho$ channel should increase dramatically, thus helping to smear out the resonance. A quantitative understanding of the disappearance of the resonance structures in photoabsorption on nuclei requires, however, also the investigation of the $2\pi$ channel.

Finally, I have shown new results for the production of positively and negatively charged kaons. The data by the KAOS collaboration could be described with no or a slightly positive mass correction for the $K^+$ and a significant lowering of the $K^-$ mass. Since this result depends crucially on the magnitude of the $K$ production cross sections in the region of 100 - 400 MeV above threshold it would be extremely important to measure these cross sections in this energy range.

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