HADRONS IN DENSE MATTER: FROM HADES TO PANDA*

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Experimental evidence for medium modifications of hadron properties is discussed. A first generation of experiments has reported interesting effects, and second-generation experiments such as HADES at GSI Darmstadt are in progress. In the future, these studies will be extended into the charm sector using PANDA, a state-of-the-art universal detector for strong interaction studies at the high-energy antiproton storage ring HESR at the future FAIR facility.

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1. Introduction

Quantum Chromodynamics (QCD) as the accepted theory of strong interactions has been extremely successful in describing phenomena in the perturbative regime at small distances or large Q^2, where the strong coupling constant α_s is much smaller than one. At larger distances, however, perturbative treatments are no more valid. Here, baryons and mesons form bound states of quarks and a rich phenomenology is still waiting for quantitative description in terms of the fundamental QCD Lagrangian. Two questions are among the most challenging: confinement and the origin of the hadron masses.

In macroscopic physics, the mass of a complex object is easily understood in terms of the sum of the constituent masses. Even in atomic and nuclear physics, this is a valid concept, if binding energy is taken into account leading to a reduction of atomic or nuclear masses when compared to the sum of the constituent masses.

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In hadronic physics, however, this picture is no more valid. Consider the mass of the proton, which is of the order of $1\,\mathrm{GeV}/c^2$. In the naive quark model, the proton consists of two up quarks and one down quark which have a total mass of less than $20\,\mathrm{MeV}/c^2$ which is much smaller than the proton's mass. From this comparison, it is obvious that other mass generation mechanisms must play a role.

In QCD, the origin of the hadron masses is related to the breakdown of chiral symmetry, one of the fundamental symmetries of the QCD Lagrangian. Explicit breaking of chiral symmetry is due to the small but non-vanishing current quark masses. Moreover, the vacuum state of QCD is highly non-trivial: the scalar quark condensate leads to spontaneous breakdown of chiral symmetry. The interaction of almost massless current quarks with the scalar quark condensate might lead to heavy constituent quarks which would then give rise to the observed large proton mass.

These theoretical concepts are very attractive but experimental verification is required. QCD inspired models [1] predict a partial restoration of chiral symmetry as a function of baryon density and temperature. The experimental challenge is then to measure the properties of hadrons in hot and/or dense hadronic matter. A variety of beams allows to scan the parameter space of hadron density *versus* temperature.

Heavy ion beams in the GSI/BEVALAC energy regime produce hadronic matter with up to 3 times normal nuclear matter density at moderate temperatures. The CERN SPS heavy ion programme explores systems at comparable density but at higher temperature. Systems with very low baryon density but at extreme temperatures are produced at RHIC and in the future at LHC. On the other hand, photon and hadron beams can be used to probe systems at normal nuclear matter density and low temperatures. It should be noted that the produced systems are extremely short-lived. In particular, for heavy ion collisions, the system undergoes rapid expansion and typical life times of the hot and dense zone created during the collision are below $10\,\mathrm{fm}/c$.

2. Experiments in the light quark sector

Here, most of the attention is focused on the light vector mesons ρ, ω, ϕ which have sufficiently short lifetimes. Thus, a substantial fraction of their decay occurs inside the hot and dense medium to be studied. By observing the decay products with suitable spectrometers, possible modifications of the hadron's mass and lifetime could be observed.

The dominant decay channels of vector mesons are hadronic but there is a small branching ratio of the order of 10^{-5} for decays into lepton pairs. This channel is of particular interest since the decay products do not undergo strong final state interaction which could distort the information on the in-medium properties of the hadron.

The first indication for medium effects has been obtained by the CERES Collaboration [2] at the CERN SPSC. CERES is a dielectron spectrometer studying lepton pairs from proton and heavy ion induced reactions between 40 GeV and the maximum SPS energy. A typical result is shown in Fig. 1. Central nucleus–nucleus collisions exhibit a strong enhancement of low-mass dilepton production as compared to $p-N$ reactions.

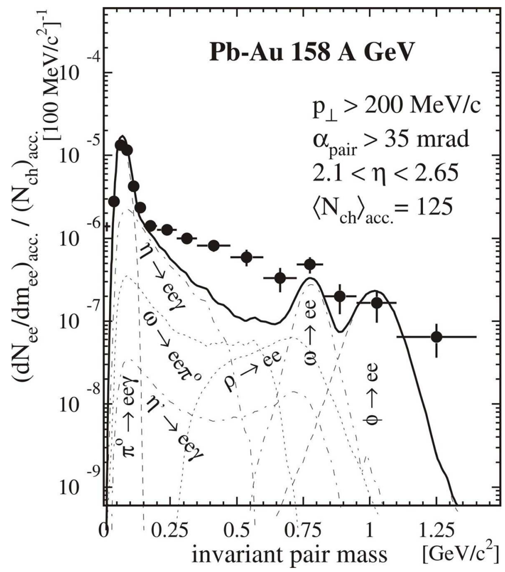

Fig. 1. CERES dielectron invariant mass distribution from 158 *A*GeV Pb + Au collisions [2] at the CERN SPS. The data is compared to the signal expected from known hadronic sources measured in $p+$ Be collisions (solid line). A large excess in the mass region below the omega meson mass is observed which can only partially be attributed to pion annihilation which is not present in the hadronic cocktail.

A large fraction of the excess is, however, due to pion annihilation, which does not contribute in $p-N$ reactions. Currently there is no quantitative description of the data using vacuum properties of vector mesons. Inclusion of in-medium modifications of vector meson properties such as a broadening and/or mass shifts of the ρ meson leads to a satisfactory agreement with the data. Unfortunately, the mass resolution of the experiment was not sufficient to separate ρ and ω mesons. NA60 [3] has recently investigated the low mass dilepton continuum at SPS energies with unprecedented statistics and mass resolution.

While CERES did study hot and dense matter, the KEK E325 experiment [4] uses $p-A$ collisions at 12 GeV beam energy, thereby probing nuclear matter at normal density. The resulting dilepton mass distribution is shown in Fig. 2 for two different targets. An access over hadronic sources

$\rho, \omega, \phi \to e^+e^-, \pi^0 \to \gamma e^+e^-, \eta \to \gamma e^+e^-$ is observed as a shoulder below the ω mass peak. Moreover, there are indications for a changed ϕ width when comparing the copper and carbon targets.

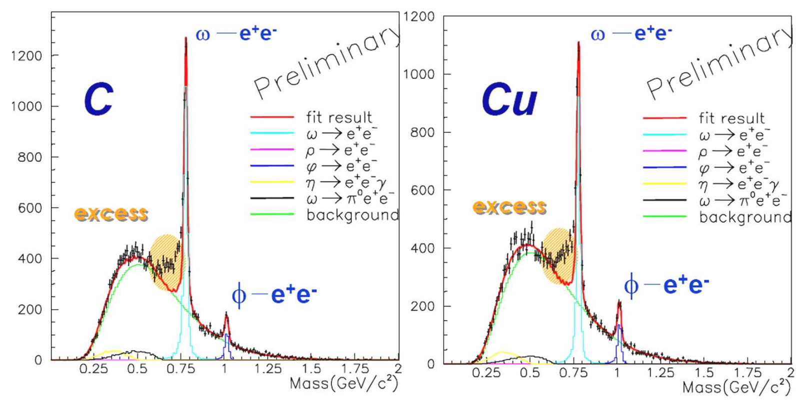

Fig. 2. Invariant mass distribution of lepton pairs measured by the KEK E325 experiment [4] in proton on carbon (left) and proton on copper (right) induced reactions at 12 GeV incident energy. An excess yield below the omega peak is observed which could be attributed to in-medium mass shifts of the omega meson.

However, it should be noted that due to the large beam energy, most of the mesons are produced with high momentum, which could lead to an enhanced fraction of decays outside the medium.

In the GSI/BEVALAC energy range, pioneering experiments were performed with the DLS spectrometer [5] at Berkeley. One of the most recent results of DLS shows a large excess of dielectrons when compared to the known sources of pion and eta Dalitz decays. The observed enhancement is much stronger than at SPS energies and also visible to a smaller extent in light ion induced reactions. No conclusive theoretical explanation exists yet, and thus there could be new physics or an experimental problem.

So far, we have only discussed experiments sensitive to the dilepton channel. As pointed out, the major advantage of these experiments is that the decay products do not undergo strong final state interaction which distorts the information on in-medium hadron properties. The drawback of these experiments is, however, that the branching ratios into lepton pairs are small. As a consequence, most experiments suffer from poor statistics.

This problem can be avoided by detecting hadronic decays. Unfortunately, the results of such experiments are model-dependent, since the effects of final state interaction cannot be neglected and need to be modeled with suitable assumptions. If an effect is observed, the question remains if this is due to medium modifications of hadrons or due to problems in understanding the details of the final state interaction.

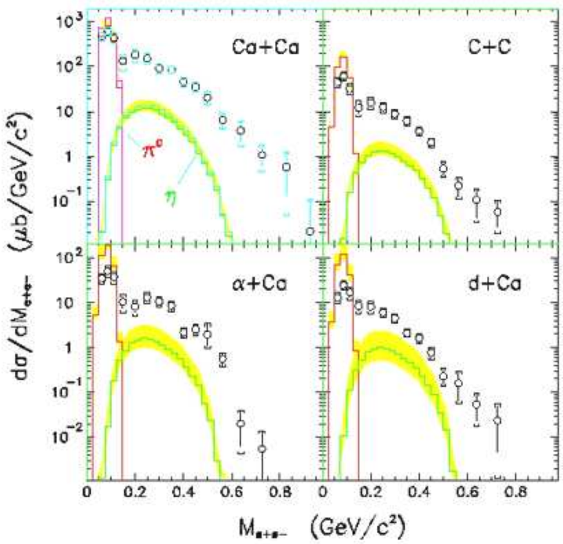

Fig. 3. Invariant mass distribution of lepton pairs for various projectiles incident on Ca targets at 1 *A* GeV, measured by the DLS Collaboration [5] at the BEVALAC. A large excess of yield in the mass region dominated by Dalitz decays of pions and eta mesons is observed, in particular for the heavy beams.

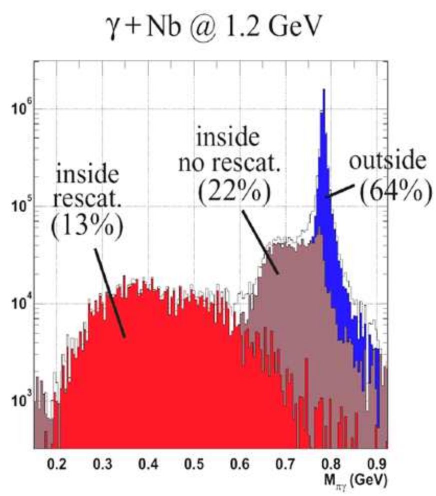

Fig. 4. The $\pi^0\gamma$ mass distribution for photon induced reactions on Nb at an incident energy of 1.2 GeV measured with the TAPS [6]. The fraction of ω mesons decaying outside the nucleus, inside the nucleus without π^0 rescattering and inside the nucleus with π^0 rescattering are indicated. The rescattering effects have been obtained from transport model simulations.

The TAPS Collaboration [6] has investigated the in-medium properties of ω mesons in photon-induced reactions by observing the decay $\omega \to \gamma\pi^0 \to \gamma\gamma\gamma$.

The resulting $3-\gamma$ invariant mass distributions (see Fig. 4) shows three features: *(i)* a broad low mass region is attributed to decays where the pion has undergone rescattering in the nucleus; *(ii)* a narrow peak corresponding to ω decays in free space is observed and *(iii)* a shoulder below the ω mass is assigned to decays of medium modified ω mesons.

In order to avoid the model dependence of the hadronic decay experiments and the low statistics and poor mass resolution of the pioneering lepton spectrometer experiments, HADES, the new high acceptance dielectron spectrometer at GSI Darmstadt exploits state-of-the art detectors and data acquisition systems combined with a powerful dilepton trigger.

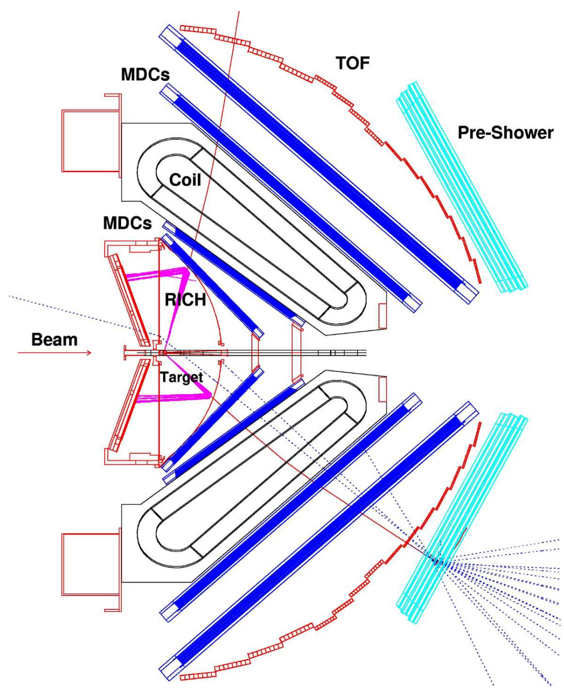

Fig. 5. Schematic layout of the HADES detector at GSI Darmstadt. HADES has a toroidal geometry with 6 sectors. A RICH detector with gaseous radiator, a carbon fiber mirror and a UV photon detector with solid CsI photocathode is used for electron identification. Two sets of Mini-Drift Chambers (MDCs) with 24 planes per sector are placed in front and behind the magnetic field to measure particle momenta. A time of flight wall (TOF/TOFINO) accompanied by a Pre-Shower detector at forward angles are used for additional electron identification and trigger purposes. For reaction time measurement, a diamond start detector is located near the target.

HADES is a rotationally symmetric large acceptance toroidal spectrometer with complete azimuthal coverage. The spectrometer acceptance covers polar angles between 18 deg and 85 deg. The angular and momentum acceptance has been optimized for the detection of dielectron decays of hadrons produced in the SIS energy regime. Momentum reconstruction is carried out by measuring the hit positions in up to 24 detector layers of the mini drift chambers (MDC). Electron identification is performed with a hadron-blind gas ring imaging Cherenkov detector (RICH) as well as via time-of-flight and shower detection. A powerful multi-level trigger system is able to select events with dilepton candidates within a selectable invariant mass window. Fig. 6 shows *preliminary* results from $2\,A\,\mathrm{GeV}$ $^{12}\mathrm{C}+^{12}\mathrm{C}$. The data is compared to QMD simulation [8] with known sources, both with and without taking into account in-medium effects. The calculation including medium effects is in better agreement with the data.

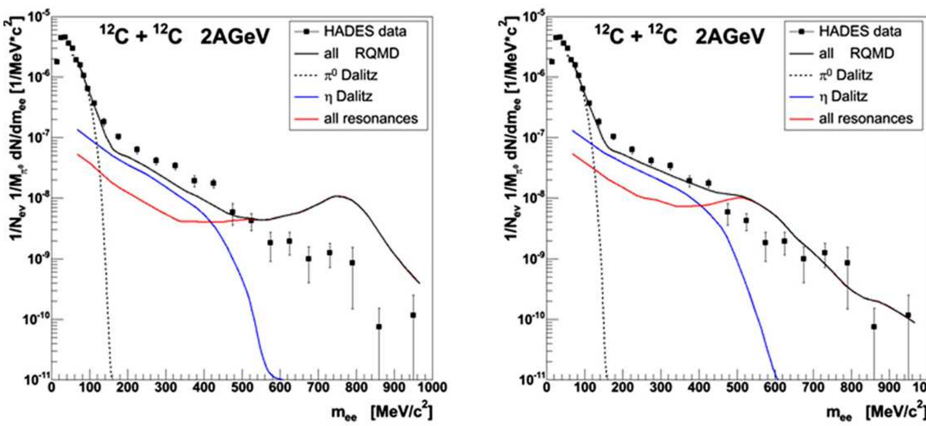

Fig. 6. Dilepton signal (black data points) after background subtraction from $2\,A\,\mathrm{GeV}$ $^{12}\mathrm{C}+^{12}\mathrm{C}$ collisions measured with HADES (preliminary results). For comparison, UrQMD simulations [8] are shown using vaccum spectral functions (left) and in-medium spectral functions (right).

Before drawing any conclusions it is, however, important to confirm the HADES lepton efficiency from the measured η Dalitz decay in proton–proton reactions. Known cross section and known invariant mass distribution allow a model-independent calibration. Moreover, both the hadronic and electromagnetic decay η can been observed, furthermore, reducing the systematic errors. Such an experiment has been recently performed and the data is in its final phase of analysis. Furthermore, a high statistics high resolution $^{12}\mathrm{C}+^{12}\mathrm{C}$ run at $1\,A\,\mathrm{GeV}$ is currently being analyzed, which can be directly compared to the DLS results.

3. Medium modifications of charmed hadrons

So far, only hadrons with u, d and s quarks have been considered. The construction of the new FAIR facility at Darmstadt will allow to extend the study of medium properties of hadrons into the charm sector.

Of particular interest are D mesons which can be considered as the "hydrogen atom of QCD". Here, a heavy charmed quark interacts with a light spectator. A reduction of the scalar quark condensate would have an effect on the constituent quark mass of the light quark. In contrast, the charmed quark mass is created via explicit chiral symmetry breaking due to the Higgs mechanism and is not expected to change significantly. Model calculations [7] using the framework of QCD sum rules predict a mass splitting for D mesons as shown in Fig. 7.

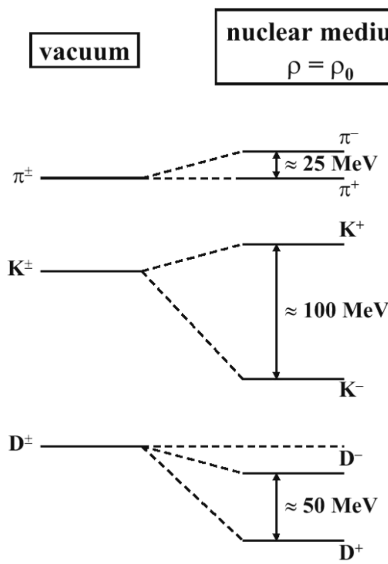

Fig. 7. Expected D meson mass splitting [7] at normal nuclear matter density, based on QCD sum rule calculations.

Possible probes include excitation functions for D production on Nuclei with antiproton beams as well as spectroscopy of Charmonium states near the open charm threshold. In-medium modifications of D mesons could influence the width of near-threshold Charmonium states. The experiment will be performed at the high energy storage ring for antiprotons (HESR), which provides high luminosity cooled antiproton beams with momenta up to 15 GeV/c . PANDA [9], a multi-purpose detector for antiproton physics is specifically designed for precision hadron spectroscopy in the charm sector. PANDA will provide:

- High rate capabilities
- Microvertexing
- Charged particle identification in a large momentum range
- Momentum reconstruction of charged particles via tracking in a magnetic field
- High resolution electromagnetic calorimeter
- Forward capabilities
- Sophisticated triggers and high performance data acquisition system

PANDA will allow to pursue a broad physics programme addressing charmonium spectroscopy, the search for QCD exotica such as glueballs and charmed hybrids, doubly-strange hypernuclei and many more aspects which are beyond the scope of this contribution.

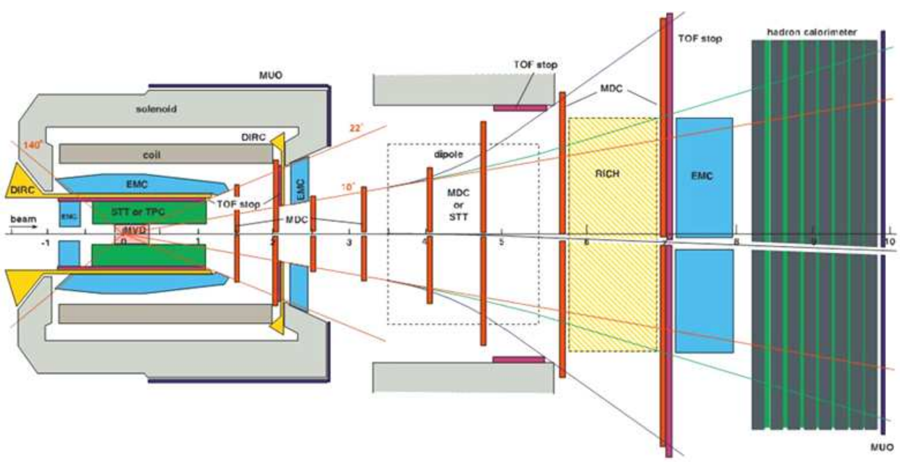

Fig. 8. Schematic overview of the PANDA detector [9], consisting of the target spectrometer with a solenoidal field and the forward spectrometer with dipole field geometry.

4. Conclusion

After many years of research, several experiments have reported first indications for medium modifications of hadron properties in dense and hot hadronic matter, which were predicted based on QCD inspired models. It remains to be seen if these effects do indeed point to a possible restoration of chiral symmetry. Further studies, using second generation experiments with improved mass resolution and rate capabilities are required to obtain a solid experimental basis for firm conclusions. In the future, the new FAIR facility at Darmstadt will allow to extend the field into the charm sector.

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REFERENCES

[1] M. Lutz, S. Klimt, W. Weise, *Nucl. Phys.* **A542**, 521 (1992).

[2] G. Agakachiev *et al., Phys. Rev. Lett.* **75**, 1272 (1995).

[3] `http://arxiv.org/abs/; nucl-ex/0501028`.

[4] K. Ozawa *et al., Phys. Rev. Lett.* **86**, 5019 (2001).

[5] R.J. Porter *et al., Phys. Rev. Lett.* **79**, 1229 (1997).

[6] J.G. Messchendorp *et al., Eur. Phys. J.* **A11**, 95 (2001).

[7] A. Hayaski, *Phys. Lett.* **B487**, 96 (2000).

[8] Shekhter *et al., Phys. Rev.* **C68**, 14610 (2003).

[9] `http://www.gsi.de/panda`.