Probing dense baryonic matter with dileptons

Joachim Stroth, for the HADES and CBM collaborations

Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt,
Max von Laue Strasse 1, 60438 Frankfurt, Germany

E-mail: `j.stroth@gsi.de`

Abstract. The role of dilepton spectroscopy in the exploration of exotic phases of nuclear matter is discussed. Special emphasis is put on the region of moderate beam energies where comparatively long-lived states of compressed matter are created. The opportunities at the future FAIR facility are outlined.

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1. Introduction

At zero temperature and in absence of strong gravitational forces nuclear matter saturates at the nuclear ground state density of 0.16 fm^{-3}. Transitions to different phases of nuclear matter can be induced in collision experiments with heavy ions in the nuclear overlap region while the matter is heated up and compressed. During the liquid to gas phase transition, the relevant microscopic degrees of freedom are nucleons [1]. The transition temperature amounts to about 6-8 MeV [2] and consequently the mean thermal energy of a constituent baryon is well below the threshold for inelastic processes (i.e. the pion mass). The transition from a hadron gas to a deconfined phase of quarks and gluons occurs at a temperature of $\simeq 170$ MeV where thermal excitation of pionic modes is copious and the confining potential substantially screened. It is characterized by a dramatic change of the microscopic degrees of freedom from hadrons to quarks and gluons [3]. This phase transition region is accessible with ultra-relativistic beam energies and currently investigated at the RHIC in the region of small net-baryon density. A phase transition to a deconfined color super-conducting phase is conjectured for the region of high net-baryon density and very low temperatures [4]. The exploration of the phase boundary and the search for an onset of confinement towards this region of the phase diagram is the goal of the experiments described here.

It has been argued that the hadron gas phase formed in heavy ion collisions can be subdivided into a region where copious inelastic collisions are rapidly changing its chemical composition and a region where the chemical composition is changed only by decay processes of the short-lived resonances [5]. The composition of the hadron gas strongly depends on temperature and density: at low temperature (or beam energy) it is dominated by the primordial nucleons, at high temperature the meson density exceeds the baryon density by factors and the baryon to anti-baryon ratio approaches unity [6]. There is sound theoretical understanding as well as experimental indications that the properties of the constituent hadrons are substantially modified in this phase [7]. The relation of these medium-modifications to a possible onset of deconfinement and a partial restoration of the chiral symmetry is a central question of modern nuclear physics. An experimental challenge is the investigation of the microscopic properties of such a resonance gas. As a matter of fact, the direct observation of resonances, or more general of short-lived hadronic states, formed in the hadron gas can only be achieved by a complete detection of their decay products. However, final state interactions of the decay products is of concern in case they interact strongly with the surrounding medium. Hadrons, which can decay into a purely leptonic final state are therefore favorable probes for hot and dense nuclear matter. Vector mesons are in particular suited as they can exclusively decay into two charged leptons. In the following section the importance of medium modifications in dielectron spectroscopy is discussed.

2. The HADES spectrometer

The HADES spectrometer, which is operational at GSI since 2002, is optimized to detect electron pairs from vector meson decay in heavy ion reactions at energies up to 2 AGeV [8]. To cope with the extremely small production probability of such pairs – i.e. of order 10^{-6} per central heavy ion collision for the lightest vector mesons ρ or ω – the detector operates at trigger rates above 10 kHz and achieves high pair acceptance of around 40%. Moreover, the spectrometer uses a second level trigger system to reject before mass storage those events, where no electron candidate was found by the on-line image processing units. To prepare such a decision, information from the ring imaging Cherenkov detector, pre-shower and time-of-flight detectors are evaluated and the respective hit information is matched between the detectors. The experimental program of HADES was started investigating $C + C$ collisions at 1 AGeV and 2 AGeV. In two production runs 650 and 220 million events where taken, respectively. A $Ca + Ca$ run at 2 AGeV is planned for this year. In parallel to the heavy ion programme, the HADES collaboration pursues an experimental programme focusing on electron pair production in elementary reaction using d, p and π beams. These measurements will provide further information to better understand the role of meson baryon coupling in the electron pair emission out of nuclear fireballs.

A first preliminary result of the HADES collaboration was presented on the INPC 2004, The the electron pair yield measured in $C + C$ collisions at 2 AGeV [9] is shown in the right panel of Fig. 1. Since the outer tracking system was not fully in place at the time of data taking, the analysis was carried out using position information behind the magnetic field from hits in the time-of-flight and pre-shower detectors only. In this way, a phi symmetric response of the spectrometer was achieved at the price of a reduced momentum resolution of $\approx 8\%$ at 500 MeV/c and an increased contribution from misidentified tracks. Electron identification was accomplished by matching identified rings in the RICH with track segments reconstructed in the drift chambers before the magnetic field. To further improve the reconstruction purity, these candidates where matched with hits in the detector systems behind the field region and by applying momentum dependent velocity conditions. The remaining contribution of misidentified tracks for this analysis amounts to about 2%. In Fig.1 the experimental data is shown together with a result obtained by analyzing the output of a UrQMD calculation, after it was propagated in the experimental setup using GEANT and corrections to simulate the detector response had been applied. Each of the two spectra is normalized to the number of reactions. For the UrQMD events, the experimental trigger condition, where a minimum of 4 active time-of-flight detector cells were required, was applied also. The systematic error due to the normalization procedure is indicated by the shaded arrow band. An additional systematic error is quoted for the the low-mass region and is the result of an imperfect modeling of the experimental detector response in the simulation. In the UrQMD simulation, only electron pairs from π^0 and η decay after "freeze-out" are treated. The results suggests that there is little room for substantial pair enhancement in the mass region between π Dalitz and vector meson decay, however, more substantial conclusions can only be drawn once the final result is available.

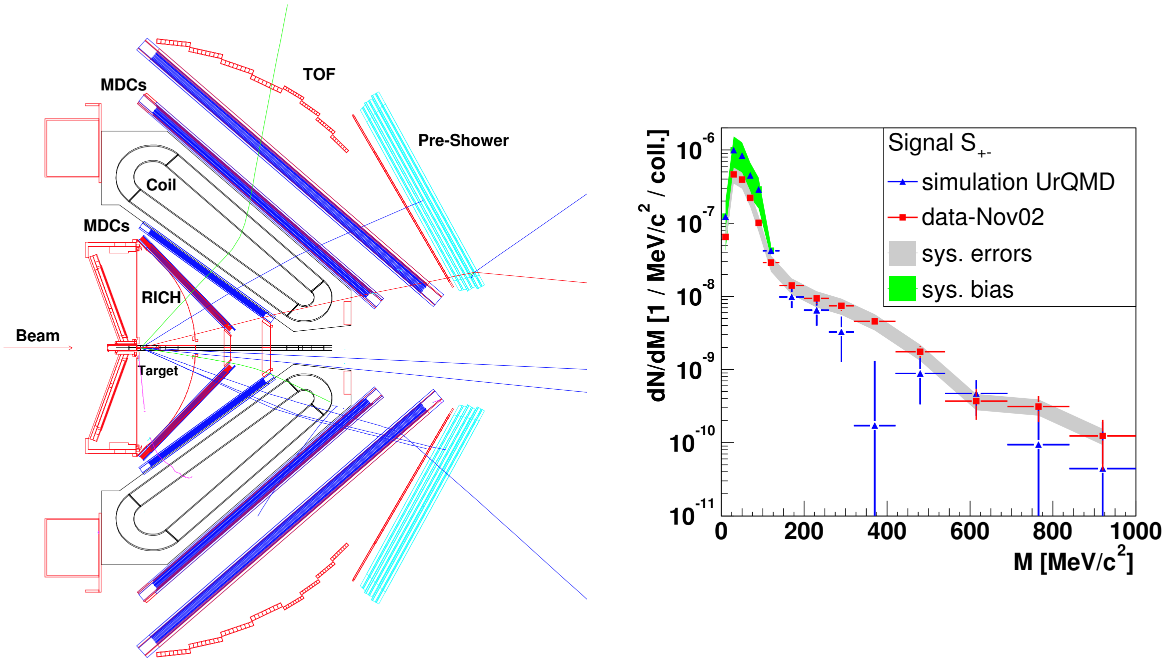

Figure 1. (**left panel**) Lateral cross section through the HADES spectrometer. Momentum measurement for charged particles is achieved by tracking the particles in front of and behind a toroidal field generated by six super-conducting coils arranged around the beam axis. In total 4 planes of low-mass multiwire drift chambers (MDC) allow to determine the particle trajectory before entering and after leaving the high-field region with a maximum field strength of 1.4 Tesla. The invariant mass of electron pairs can thus be reconstructed with a resolution of around 1% in the low mass vector meson region. For on- and off-line electron identification a ring imaging cherenkov detector with a solid CsJ photo cathode (RICH) is used. It is supplemented by a electromagnetic pre shower detector in the forward hemisphere to further discriminate against fast pions. General particle identification is accomplished by a time-of-flight system (TOF). The tracks shown stem from an omega decay in the target region as simulated in the GEANT framework. (**right panel**) Experimental (circles) and simulated (triangles) invariant mass distribution of electron pairs from $C+C$ collisions at 2 AGeV. The colored bands indicate systematical uncertainties, the error bars of the data points refer to statistical uncertainties.

3. Dilepton spectroscopy at FAIR

In the comming years HADES will fully exploit the possibilities of dielectron measurements in heavy ion collisions up to 2 AGeV. With the upcoming new facility FAIR, a new possibility to systematically study the microscopic properties of dense baryonic matter up to beam energies of 35 AGeV will open. Measurements will be possible in an energy range, which was not used for such studies before and a full excitation function for electron pair production up to the lowest SPS energies will be within reach. According to the current FAIR project plans the 100 Tm will be operational a few years before the 300 Tm ring will deliver heavy ion beams up to energies of 35 AGeV. Monte Carlo studies have shown, that the HADES spectrometer is able to run also at energies of 8 AGeV and with medium heavy nuclei.The then increasing boost in the laboratory frame of particles moves the accepted phase space to the backward rapidity region and thus the apparent particle multiplicity in the spectrometer at tolerable values.

For the higher beam energies, measurements will be conducted with the new CBM spectrometer [10]. This multi-purpose detector, which is described elsewhere in this volume,

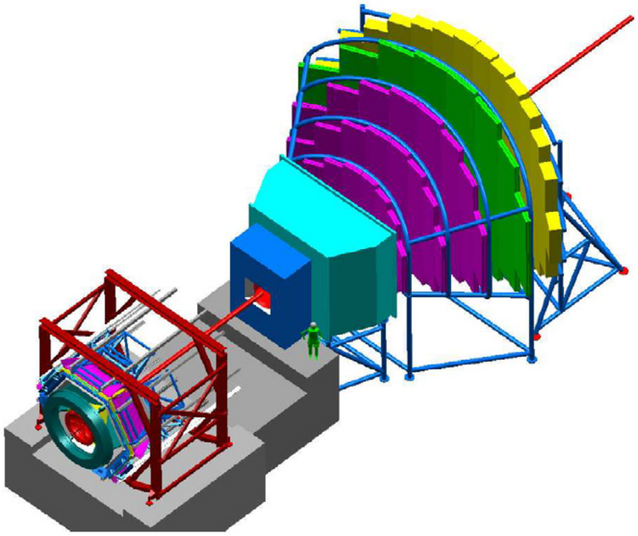

Figure 2. Layout of the experimental setups forseen for dense matter physics at the future accelerator laboratory FAIR. Behind the HADES spectrometer the future CBM experiment is seen. It combines a compact tracking sation in a strong magnetic dipole field with Cherenkov, transition radiation, resistive plate detectors and a calorimeter (see contribution to this volume).

is designed to accomplish this task using a completely different approach than HADES. The concept is to perform tracking of all charged particles emitted from the reaction zone directly behind the target in a compact magnetic field using silicon pixel/micro-strip detectors. Detectors needed for particle identification will follow behind. For electron identification a RICH detector and several planes of transition radiation detectors are foreseen. At these higher energies, efficient π rejection is a crucial issue. To achieve this the active (track by track) recognition of background events from π^0 decay is mandatory. Since the electron pairs from such decays are opened up in the magnetic field before reaching the PID detectors, these tracks will have to be rejected by means of their topology. Hence, efficient tracking of all charged tracks with high resolution has to be achieved. The optimal design of a silicon tracking system for this task is currently a matter of detailed simulation studies. With the high rate capability and a momentum resolution of $\simeq 1\%$ at 1 GeV/c momentum, systematic investigation will be possible. The option to run CBM as a muon spectrometer is currently also investigated.

4. Summary

An experimental campaign to systematically investigate the microscopic properties of hadrons in dense nuclear matter with penetrating probes has been started at GSI in 2002 with the going-online of the HADES spectrometer. With the future FAIR facility such experiments can be conducted up to beam energies of 35 AGeV. The planned CBM experiment will address electron pairs, then extending the measurements up to the J/Ψ mesons, as one essential observable but also concentrate on open charm production and other observables accessible through hadronic final states.

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