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STUDYING IN-MEDIUM HADRON PROPERTIES WITH HADES*

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HADES is a second generation experiment designed to study dielectron production in proton, pion, and heavy ion induced reactions at the GSI accelerator facility in Darmstadt. The physics programme of HADES is focused on in-medium properties of the light vector mesons. In this contribution we discuss relevance of dielectron spectroscopy to the problem of hadron mass origin. We present status of the HADES experiment, demonstrate its capability to identify rare dielectron signal and show first experimental results obtained from C+C reactions at 2 AGeV.

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1. Introduction

One of the most intriguing problems in modern physics is the particle mass generation mechanism. In the standard model, massless fermion fields acquire mass via interaction with the Higgs field. For example, the current quark masses from $m_q = 5$–10 MeV$/c^2$ for the u, d up to 180 GeV$/c^2$ for the heaviest top quark result from this interaction. However, for the light u, d, s quark flavors, an additional mechanism is introduced to account for the large u, d, s constituent masses. It is connected to the phenomenon of spontaneous breaking of Chiral Symmetry (CS), a global symmetry of Quantum Chromo Dynamics (QCD) exactly valid in the limit of massless quarks [1]. Conservation of the CS would lead to decoupling of left-handed and right-handed quark interactions and to mass degeneration of hadrons with opposite parities (as for example for $J = 1$ mesons $\rho(770)$ and $a1(1260)$). The spontaneous breaking of chiral symmetry is caused by a non-trivial feature of the QCD vacuum, namely the existence of a scalar quark condensate $\langle\bar{q}q\rangle$. The interaction of current quarks with the condensate is responsible for the large constituent quark masses. The condensate's expectation value can be estimated assuming SU(2) flavor symmetry, $\langle\bar{q}q\rangle = -(240\text{MeV})^3 = -1.8\text{fm}^{-3}$, based on the Gell-Mann–Oakes–Renner relation [2] linking the expectation value of the condensate to the properties of the pion, the Goldstone boson of spontaneous symmetry breaking. The quark condensate's properties in nuclear matter are known in a model independent way only at low densities and zero temperature where one can treat nucleons as independent objects:

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} = 1 - \frac{\sigma_{\pi N}}{f_\pi^2 m_\pi^2}\rho\,. \tag{1}$$

Here ρ is the density of nucleons, $\sigma_{\pi N} = 49 \pm 8$ MeV is the pion–nucleon-sigma term and $f_\pi = 93, m_\pi = 140$ MeV are pion decay constant and mass, respectively [3–5]. This relation indicates that already at normal nuclear matter density a $\sim 30\%$ reduction of the condensate can be expected. A description of the quark condensate as a function of temperature and density has been obtained in model calculations as for example in [6] within the Nambu–Jona-Lasino framework. Moreover, the temperature dependence has been obtained from lattice QCD calculations [7]. From these calculations one can conclude that the quark condensate drops almost linearly with the nuclear density and vanishes at $\rho = 4$–$5\rho_0$. The evolution of the quark condensate along the temperature axis (ρ=0) differs from the density dependence. A sudden drop of the condensate at a critical temperature of $T = T_{\rm c} \approx 150$ MeV coincides with the temperature of the phase transition from a normal to a deconfined phase of hadronic matter [8–10].

The experimental observation of this phase-transition is the aim of ultra-relativistic heavy ion collisions. One of possible observables proposed in this context are spectral functions of hadrons inside nuclear matter. A simple scaling law was proposed by Brown and Rho who related change of the condensate vacuum value in the nuclear matter to respective change of hadron masses [11]:

$$\frac{M_h^*}{M_h} \sim \frac{m_V^*}{m_V} \sim \left(\frac{\langle\bar{\psi}\psi\rangle_\rho}{\langle\bar{\psi}\psi\rangle_0}\right)^{1/3}, \tag{2}$$

where M_N^*, m_V^* are the nucleon and the vector meson masses inside nuclear matter. According to this formula, the dropping of hadron masses should be a direct consequence of a reduction of the expectation value of the chiral condensate in dense and/or hot nuclear matter which can be considered as a signal of chiral symmetry restoration. One should also note that according to relations 1 and 2, precursor phenomena can be expected even at moderate densities below the phase transition region.

2. Dilepton spectroscopy

For several reasons, the light vector mesons $\rho^0/\omega/\phi$ can be considered as key candidates to probe the density and energy dependence of the chiral condensate. From the experimental point of view we shall discuss two of them: (a) live times and (b) dilepton decay branches. The life times of vector mesons range from $\tau = 1.3$ fm/c for ρ and $\tau = 24$ fm/c for ω to $\tau = 44$ fm/c for ϕ. The τ for ρ meson is shortest and significantly smaller as compared to the mean fireball life time of $\tau \approx 10$–15 fm/c at beam energies $E = 1$–5 AGeV [12, 13]. Hence, once the ρ meson is produced in an early stage of a heavy ion collision, it will most likely decay inside the fireball volume. In this context, the special role of low energy 1–2 AGeV collisions should be stressed. Although the densities (and temperatures) achieved at these energies are moderate (~ 2–$3\rho_0$), the production of mesons is strongly bound to the high density region of the collision. This is so because collision energies are well below the production thresholds in direct nucleon–nucleon collisions and multi-step processes with intermediate pion production are required for heavy meson production [12]. Furthermore, the quantum numbers of vector mesons are identical to the photon, thus they can convert into dilepton pairs with sizable branching ratios of the order of 10^{-5}. This decay mode is of particular importance since dileptons do not interact strongly with the surrounding hadronic matter and leave the reaction zone unperturbed, thus allowing for the undistorted reconstruction of the invariant mass of a particle [14–18] decaying inside hadronic matter.

Dielectron (e^+, e^-) production has been studied in ultra-relativistic collisions at CERN/SPS as well as in the SIS/GSI regime at the Bevelac. The high temperature regime was studied in ultra-relativistic heavy collisions at CERN by the CERES collaboration. A large dielectron excess below the ρ–ω region was observed as compared to properly scaled yields from p-Be reactions [19]. Although a big portion of this enhancement could be attributed to pion–pion annihilation, the measured yields could only be satisfactory explained if significant in-medium ρ meson modifications were assumed. Unfortunately, two classes of theoretical models were equally successful in describing the data and therefore final conclusions cannot be made yet. The first class of models is based on the the dropping mass scenario proposed by Brown and Rho based on chiral symmetry restauration. Alternatively, there are models which predict ρ meson mass modifications to occur as a result from hadronic ρ-baryon interactions. In particular, the strong $\rho - N^* N^{-1}$ particle–hole coupling, where N^* is a low-lying nucleon resonance $(N^*(1520), \Delta(1700), N^*(1720), \ldots)$ was found to be the most dominant origin of a considerable shift of the ρ meson mass (for a review, see [22]). The important difference of these two types of model calculation is that absolute dielectron yield in the ω-ϕ mass region differs by factor 5. Unfortunately, the present quality of the data cannot distinguish between these two scenarios.

Moreover, dielectron invariant mass distributions were measured in proton–proton, light and heavy ion reactions in 1–2 AGeV energy range by the DLS collaboration at the BEVELAC [20,21]. Within the given experimental error bars the extracted e^+e^- production rates in proton–proton reactions could be well reproduced by theoretical calculations assuming free dielectron decays of various hadronic sources. For the heavy-ion collisions Ca+Ca and C+C a remarkable excess of the dielectron yield in the low mass range 200 MeV/c^2 $< \mathrm{M}_{\mathrm{inv}} <$ 600 MeV/c^2 as compared to the theoretical calculations was found [23]. In contrast to the CERES experiment, this dielectron excess cannot be explained by existing models based on medium modified ρ meson spectral functions or by the Brown–Rho scaling [23, 24].

The HADES experiment [25,26] described below aims at systematic studies of dielectron production in proton, pion and heavy ion induced reactions. Although beam energies available at GSI/SIS facility are limited to a region near the vector meson production threshold, this domain is of large interest both for confirming the unexplained DLS results as well as for the understanding of the importance of vector-meson hadronic couplings involved in interpretation of the CERES data. Moreover, the experiment will allow for the first time to measure the most important reaction channels in nucleon–nucleon and pion-induced experiments in exclusive kinematics.

3. The HADES experiment

HADES (High Acceptance Dielectron Spectrometer) is a magnetic spectrometer recently commissioned at the heavy ion synchrotron facility SIS at GSI Darmstadt. It is designed for high resolution and high statistics dielectron spectroscopy in pp, pA, AA and πp, πA reactions in the 1–2 AGeV energy range. A comparison of the dielectron invariant mass spectra from πp and pp reactions with pA, πA and AA-collisions will allow to study vector meson spectral functions as a function of nuclear matter density and size of the collision system with an excellent mass resolution and good statistics.

As it has been mentioned above, the dielectron decay channels of the vector mesons are suppressed by a factor of $\approx 10^{-5}$ as compared to hadronic decays. Thus, in a typical AA reactions at SIS energies the expected total yield of dielectrons from the vector meson decays is about 10^{-6} per central event [12, 13]. Thus, the experimental challenge is to find one dielectron in one million of these central collisions each containing background of charged hadrons and photons from π^0-decays. This requires a system with large geometrical acceptance, high rate capabilities, sufficient granularity and a highly selective multi-stage trigger scheme with real time electron recognition. For a fast electron recognition, detectors with good electron/hadron separation power and dedicated trigger schemes involving image processing are necessary. Moreover, an excellent invariant mass resolution $\delta M/M \approx 1\%$ is required for vector meson identification.

HADES, shown in figure 1, is a rotationally symmetric, large acceptance toroidal spectrometer with complete azimuthal coverage [27]. The spectrometer acceptance covers polar angles between 18° and 85°. The angular and momentum acceptance has been optimized for the detection of dielectron decays of hadrons produced in the SIS energy regime. The dielectrons from such decays are emitted over the whole solid angle but with a maximum probability near $\theta = 40°$. For dielectron invariant masses $M < 1.5$ GeV/c^2 and transverse momenta $p_{\mathrm{T}} < 1.5$ GeV/c this geometry results in a flat acceptance. The achieved geometrical acceptance of $\sim 40\%$ represents an improvement by a factor of 100 as compared to the pioneering experiments performed with the DLS spectrometer at Berkeley.

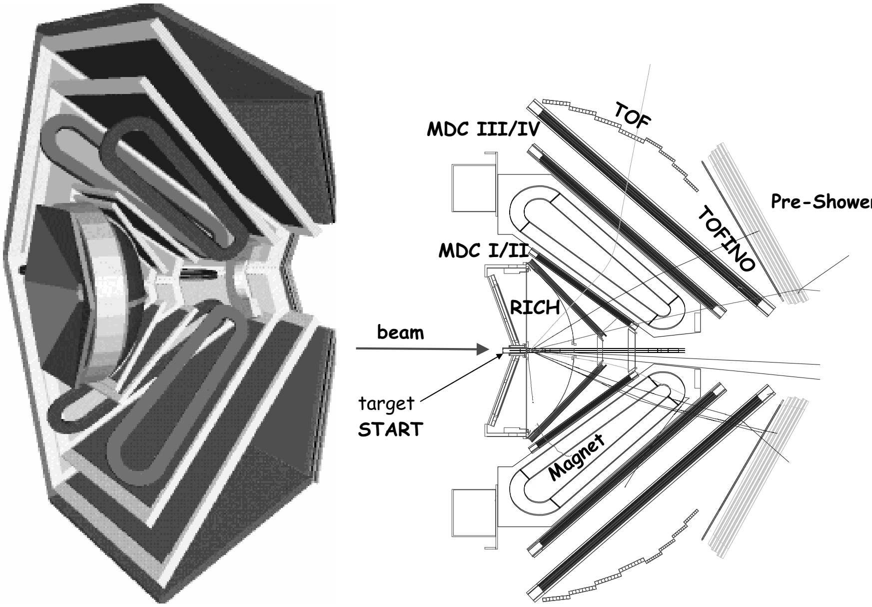

Fig. 1. Left: three dimensional artist's view of the HADES spectrometer (two sectors has been removed for clarity). Right: Side view of HADES. The RICH detector, consisting of a gaseous radiator, a carbon fiber mirror and a tilted photon detector is used for electron identification. Two sets of Multi wire-Drift Chambers (MDCs) 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 an additional electron identification and trigger purposes. For a reaction time measurement, a start detector is located near the target.

Reconstruction of the dielectron four-momentum vectors is carried out by measuring the hit positions in several detector layers and their assignment to electron and positron tracks. The electron hits are identified in special electron detectors placed in front of (RICH) and behind (TOF, TOFINO, Pre-Shower) the magnetic field. They are matched with hits reconstructed in the Multi wire Drift Chambers (MDC). More precisely, the electron track recognition and the dielectron invariant mass reconstruction consist of three major steps:

(1) A first electron identification is obtained in a fast RICH with a gas radiator (Ring Imaging Čerenkov Counter) [28, 29] surrounding the target in the forward hemisphere. The selection of a gaseous low Z radiator ensures complete hadron blindness of the detector as well as low multiple scattering and hence allows for determination of the elec-

tron track emission direction. Electrons with velocities $\beta \approx 1$ radiate Čerenkov light in a cone along their tracks through the radiator. The light is reflected by a carbon fiber mirror and is focused as a ring image on a position sensitive photon detector (PD) plane. The PD is a multi wire proportional chamber (MWPC) with a CsI solid photo cathode for photon-electron conversion, which is sensitive in the ultraviolet region.

(2) Track momentum is reconstructed from the deflection in the magnetic field. The track deflection is calculated from the directions of two track segments reconstructed in both the MDC systems [30]: I/II placed in front and III/IV behind the magnetic field. The MDC chambers consist of six wire planes and are filled with a helium-isobuthane gas mixture. The total thickness of the four MDC chambers amounts to $x/X_0 = 2 \times 10^{-3}$ only and is comparable to the contribution of the air volume between the target to the MDC IV. The designed invariant mass resolution of $\delta M \approx 1.0\%$ is achieved in a given field configuration with a position resolution of $\delta y \leq 100$ μm (σ).

(3) Redundant identification of the electron tracks is achieved via time of flight measurement in a set of scintillating detectors arranged in two subsystems: TOF and TOFINO forming the Multiplicity and Electron Trigger Array (META) [26,31]. The inner TOFINO detector is accompanied by a Pre-Shower detector registering electromagnetic showers of traversing particles. The second electron identification is necessary since a large fraction of electron pairs originate from γ-ray conversions in either the target or the RICH radiator or from π^0 Dalitz decays. These pairs consist of low momentum electrons from which frequently none or only one from a pair manages to traverse the magnetic field, reaching the META detector. Nevertheless, since the multiplicity of these pairs is larger than one in typical electron event, electrons from different decay vertices can still be combined into false dielectrons and hence form a combinatorial background. A rejection of this background is one of most difficult problems in dielectron spectroscopy. In the HADES experiment these close pairs can be efficiently rejected by their reconstruction in front of the magnetic field in the RICH and the inner MDC I/II detectors.

The data acquisition is started by a positive first level trigger (LVL1) decision. The first level trigger is obtained by a fast $t_{\mathrm{f}} < 100$ ns hardware analysis of the multiplicity measurement M_{ch} performed by the TOF and TOFINO modules. The second level trigger (LVL2) performs a three step process [32]. In the first step a search for electrons ring images on the

RICH pad plane is made. In parallel, charge clusters with the signature of an electromagnetic shower in the Pre-Shower detector as well as particles with an appropriate time of flight in the scintillator TOF wall are searched. The resulting position coordinates of electron candidates in the inner RICH and outer META detectors are compared in the Matching Unit (MU) in an appropriate matching window that takes into account the track deflection due to the magnetic field. The matched hits define valid electron candidate track. In the third step the selected electron tracks with opposite charges can be combined into dielectron pairs and their invariant mass can be calculated basing on a look-up table which contains a mapping of the polar electron track deflection angles to momenta. In the presently investigated 2 AGeV C+C collisions a conservative LVL2 trigger condition was imposed requiring at least one electron track which provided 92% background event rejection and high electron identification efficiency ($\varepsilon \geq 0.7$).

The performance of the spectrometer was studied in several commissioning beam times by means of the C+C reaction. The typical beam intensity was $I = 10^6$ particles/s and a 5% interaction length target was used. In the recent two experimental runs in 2001 and 2002 we collected around 5×10^7 and 20×10^7 LVL1 triggered events, respectively. In the second run we used for a first time LVL2 trigger to select LVL1 events with electron tracks.

Particle identification in the HADES detector started with track reconstruction in the MDC detectors. The MDC track segments were correlated with corresponding hits in the META after the magnetic field, in order to determine the momentum of particles (no MDCIII/IV were used in the presented below analysis). Hadron identification is performed mainly on the basis of the measured momentum, velocity and energy loss in the TOF detector. The principle of the hadron identification is illustrated in figure 2. Particles with different mass fill different regions in the velocity vs. momentum distribution. The pronounced maxima correspond to positive/negative pions protons and deuterons. The proton and pion yields were extracted and found to be in agreement within 10% with those values obtained by the analysis of the URQMD simulation data.

For the analysis of electrons the key detector is the RICH. The charged particle tracks were matched with ring centers. The matching condition was $\Delta\theta < 1.7^\circ$ and $\Delta\phi \sin\theta < 1.8^\circ$ for the polar and the azimuthal angles, respectively. For additional electron identification, the following condition on the velocity of particles was applied: $0.8 < \beta < 1.2$ as determined by the TOF and $0.8 < \beta$ by the TOFINO. The asymmetric β cut in TOFINO has been chosen since the lower granularity of this detector results in $\sim 20\%$ double hits. In these cases the determination of the time of flight is not correct and leads to $\beta > 1.0$. The resulting momentum *versus* velocity distribution after electron identification cuts is showed in figure 2 (right), exhibiting a clear electron signal. The detail investigation of electron distributions reveals that the residual contamination of hadronic background is less than 2%. Furthermore, the shape of the momentum spectra for electrons and positrons are very similar with an average multiplicity of 2×10^{-2} per LVL1 event. Measured multiplicities agrees with the simulated ones within 30%.

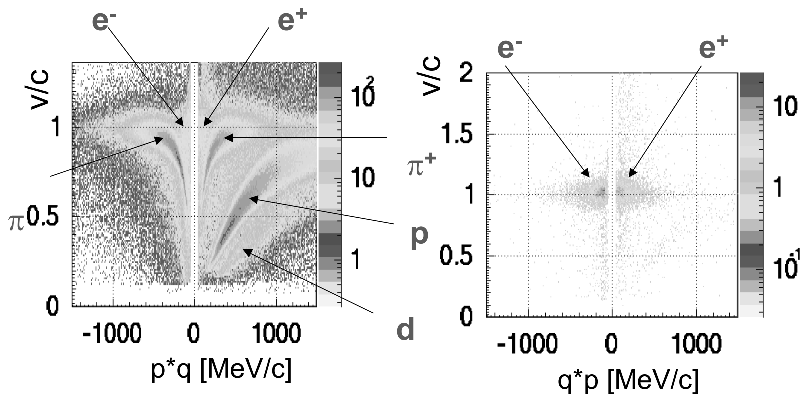

Fig. 2. Left: Velocity *versus* sign(charge)*momentum correlation for all reconstructed tracks from C+C at 2 AGeV collisions. Pion and proton branches are clearly resolved. Right: same as on the left but with additional condition on electron identification. Intensity scale is logarithmic.

From the identified electrons we have constructed unlike (e^+e^-) and like sign (e^+e^+, e^-e^-) pairs. For further analysis we have used only pairs that contain electron tracks producing well separated hits in all detectors and with opening angles larger than 4°. Most of them are due to combinatorial background arising from multiple photon conversions and Dalitz decay of π^0 mesons. In order to evaluate the combinatorial background $N_{\rm com}$ we have used like-sign pairs N_{++}, N_{--} and formula $N_{\rm com} = 2\sqrt{N_{++} * N_{--}}$. Figure 3 (left-hand side) shows unlike sign invariant mass distributions together with the corresponding combinatorial background. The expected most dominant sources of dielectron pairs are π^0 and, to a much smaller extent, η Dalitz decays. We observe indeed that the dominant signal is in the invariant mass region up to 150 MeV/c^2. In the higher mass region, shown on right-hand side of figure 3, we also observe a systematic excess of dielectron yield over the combinatorial background with an average 1:8 signal to background ratio. A more advance analysis using close pair rejection is in progress now. Preliminary results indicate that further significant (2–3) background reduction can be anticipated. The total pair statistics, after subtraction of combinatorial background and analysis cuts described above, amounts to $\sim$ 5k in the run with LVL1 trigger but and is almost one order of magnitude larger in the recent run where the LVL2 trigger was used.

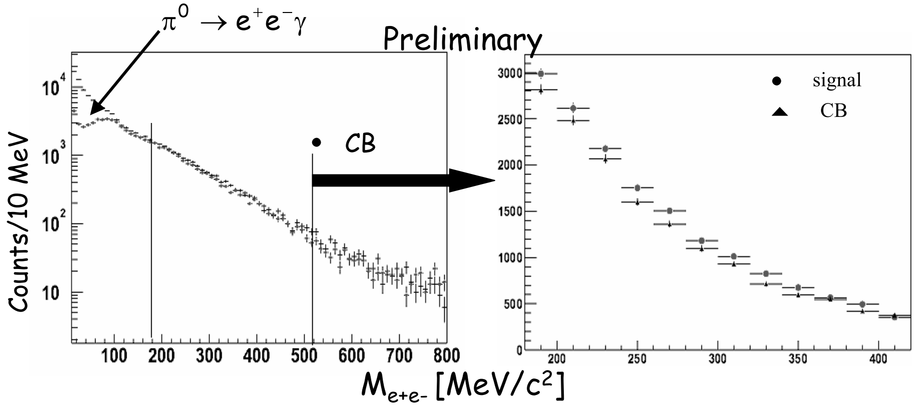

Fig. 3. Left: Dielectron invariant mass distribution and combinatorial background, calculated as described in the text, measured in 2 AGeV C+ C collisions. Right: same as on the left but in linear scale for $0.4 > M_{e^+e^-} > 0.15$ GeV/c^2.

4. Summary and outlook

The HADES spectrometer offers a unique possibility for systematic studies of the light vector meson spectral functions by means of dielectron spectroscopy. Recent results from commissioning runs confirmed the expected superior on-line and off-line electron identification capabilities. In particular, a high-statistics run with LVL2 trigger provided first pair data from C+C reactions at 2 AGeV. High resolution dielectron spectroscopy becomes also now possible after completion of the outer tracking system. First experiments aiming in the exclusive ω and η meson reconstruction in proton–proton reactions are planned for the upcoming year.

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