Exploring hot and dense QCD matter with HADES

Georgy Kornakov for the HADES Collaboration

Wydzia l Fizyki, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland
E-mail: georgy.kornakov@cern.ch

Abstract. Experiments at $\sqrt{s_{NN}} = 2 − 3$ GeV provide the lowest energy point of the global effort made by the heavy-ion community in order to map the QCD phase diagram. This correspond to the highest baryon chemical potential, 700-900 MeV according to the universal freeze-out curve, and temperatures of the fireball of 60-80 MeV. The formed matter can be characterized in terms of particle spectra, fluctuations and correlations. The dilepton spectrum is dominated by thermal emission from the medium and it is sensitive to in medium hadron properties. Strangeness production occurs below the free nucleon-nucleon threshold and it is a sensitive probe to test models of strangeness propagation in matter and its coupling to baryons. Data show a common scaling of measured yields as a function of number of participating nucleons independently on the strangeness content or mass of the hadron. Strangeness propagation in cold nuclear matter produced in pion induced reactions on heavy and light targets shows a significant absorption of negative kaons in heavy targets as well as a similar behaviour of $\phi$ indicating a strong coupling of $\phi$ with nucleons. Two-pion correlations, flow harmonics, fluctuations are explored as well in order to further pin down the properties of the created matter.

1. Introduction

Nuclear matter exists in a compressed and heated state during neutron star merger. Various models suggest that temperatures of 50–80 MeV and densities around twice the nuclear ground–state density might be reached [1]. Understanding the properties and structure of the dense and hot QCD matter is crucial for answering fundamental questions on the origin of heavy elements in the Universe. Recent observations of ejecta from a single neutron star merging process seems to confirm the previously predicted importance of this process. Such a mechanism could account for many heavy elements around us [2, 3].

Similar conditions to those in neutron-star mergers can be recreated in the laboratory by colliding heavy nuclei at relativistic energies [2]. The formed matter provides controlled and reproducible access to study the structure of QCD matter. The properties can be studied using particle spectra of rare and penetrating probes, resonances or production yields of strange hadrons. Measurements of collective motion and particle correlations allow one to access the dynamical evolution of the emitting source.

For that purpose the High Acceptance DiElectron Spectrometer (HADES) conducts experiments with heavy-ion and elementary particle (p, $\pi$) beams at the SIS18 synchrotron at GSI in Darmstad, Germany. These beams are collided with targets placed within the HADES detector. The interaction length is chosen such that the triggered event rate is about 50 kHz for elementary reactions and 10-15 kHz for heavy-ion beams. The angular acceptance in the beam direction covers from 15$^\circ$ to 85$^\circ$ and 85 % in azimuth, corresponding the rest to the frames and coils of the six superconducting magnets which provide a strong magnetic field used to
products of electromagnetic decays of collisions, those radiated from the hot and dense medium, and finally those corresponding to sources contributing to the spectra can be classified as dileptons emitted from primordial NN collisions in order to neutralize the system-size dependence is shown in Fig. 1. The different matter. The measured invariant-mass distribution normalized to the multiplicity of a heavy-ion collision, yet the emission from the hot and dense stage is dominant according to a consequence of the partial restoration of chiral symmetry due to the compressed and heated ρ models, (see [6] and references therein). The strong modification of the properties of the created system, fluctuations or intensity interferometry sensitive to the three-dimensional emitting source. A selection of recent results focused mainly on Au+Au data which are displayed as vertical lines and boxes, respectively. Blue squares are the reference NN measurement scaled to the same number of π0. The cyan curves represent the electromagnetic decays of π0, η, ω and φ. Right: dilepton excess yield. Displayed is the acceptance corrected spectra after subtracting the previously mentioned sources together with the fit for extraction of the black-body radiation temperature in the intermediate mass region and model predictions for the spectral shape of the ρ. Figures are taken from [6].

bend the trajectories of charged particles for momentum measurement. These trajectories are reconstructed with two stations of drift chambers in front of and two behind the magnet. Particle identification is performed by means of the Time-of-Flight method combined with the specific energy loss measurement in the tracking detectors. Electrons and positrons are required to have an additional coincident Cherenkov ring in the RICH [4] detector. The azimuthal orientation of the collision is reconstructed from the signals of the Forward Wall hodoscope located 7 meters downstream the target. This detector can also be used to measure the percentage of overlap of the collision or centrality. Another estimator is based on the number of signals from the Time-of-Flight detectors [5].

The experiment provides a complete set of observables, e.g., multi-differential particle spectra as dileptons, particles with strangeness or baryon resonances as well as measurement of collective properties of the created system, fluctuations or intensity interferometry sensitive to the three-dimensional emitting source. A selection of recent results focused mainly on Au+Au data which are shown hereafter.

2. Particle spectra
The dilepton spectrum reflects the integral production over space-time of the full evolution of a heavy-ion collision, yet the emission from the hot and dense stage is dominant according to models, (see [6] and references therein). The strong modification of the ρ can be interpreted as a consequence of the partial restoration of chiral symmetry due to the compressed and heated matter. The measured invariant-mass distribution normalized to the multiplicity of π0 in Au+Au collisions in order to neutralize the system-size dependence is shown in Fig. 1. The different sources contributing to the spectra can be classified as dileptons emitted from primordial NN collisions, those radiated from the hot and dense medium, and finally those corresponding to products of electromagnetic decays of π0, η, ω and φ. The measured spectra after the subtraction of the first and last type of sources is called excess radiation and is shown in the same figure.
Figure 2. Left: Example of reconstruction of K\(_0\)\(_s\) and Λ signals in 0-40 % Au+Au collisions. The shaded area shows the combinatorial background obtained with the event mixing technique, afterwards subtracted to obtain the yield in every phase-space bin. Middle: Reduced transverse mass spectra of K\(_0\)\(_s\) (left) and Λ (right) for the 0-40 % most central events. The dotted curves are fits to the data used to extract the yields. Right: Multiplicities per mean number of participants Mult/(A\(_{\text{part}}\)) as a function of (A\(_{\text{part}}\)). All strange hadron yields are fitted simultaneously with a power function with the result: α = 1.45 ± 0.06. The figures and more details of the analysis can be found in [7].

Surprisingly, the remaining yield has an exponential shape with a Boltzmann slope parameter of kT = 71.4±2.1 MeV. Such a distribution can be described assuming in-medium strongly broadened ρ mesons. More details on the analysis and interpretation of the results can be found in [6].

Strangeness production at \(\sqrt{s_{\text{NN}}} = 2.42\) GeV is produced below the nucleon-nucleon threshold. Therefore, the production is a very sensitive probe to tests different mechanisms. Strangeness is produced rarely at these energies, but the reconstruction capabilities of the detector together with the large data sample allow one to perform a multi-differential reconstruction. In Fig. 2 an example of the reconstructed invariant mass spectra of K\(_0\)\(_s\) and Λ are shown together with the differential distribution of the yield as a function of the measured transverse mass. The production yields as a function of the mean number of participant was found to be independent of the quark content or production threshold at this energy [7, 8].

In order to probe the mechanisms of strangeness propagation in nuclear matter, specially K\(^-\) and φ absorption, \(\pi^-\) induced reactions on C and W targets has been studied at an incident beam momentum of 1.7 GeV/c [9]. The differential cross sections of K\(^-\) and K\(^+\) produced off C and W are shown in Fig. 3. Also shown are the rapidity distributions and the double ratios of the cross sections of negative and positive kaons in tungsten normalized by the ratio in carbon in the same figure. The double ratio is found to be 0.319 ± 0.009, manifesting larger absorption of K\(^-\) in W than in C. The measured φ/K\(^-\) ratios in C and W are 0.55 ± 0.04 and 0.63 ± 0.06 indicating similar absorption for the φ as for the K\(^-\) and thus existence of a strong φN coupling [9].

A significant fraction of nucleons are excited into resonant states such as Δ and N\(^*\) in Au+Au collisions at \(\sqrt{s_{\text{NN}}} = 2.42\) GeV. The lifetime of these states is several times shorter than those of the fireball. Therefore, the excitations and decays are occurring within the strongly interacting dense medium. Baryon spectral functions are predicted to be strongly modified as a function of temperature and density [10]. Moreover resonances play a key role in the
medium modification of vector meson spectral lines [11] and in the medium propagation of strangeness below nucleon-nucleon production threshold [12]. In addition, the decay products of the baryon resonances undergo subsequent interactions with the surrounding medium giving rise to competing recreation or absorption processes repeating several generations of the $\Delta \leftrightarrow \pi + N$ cycle. In order to understand better all these mechanisms and dynamics of the evolution of the compressed and heated QCD matter the direct reconstruction of the baryonic resonances is desirable and has been achieved by HADES.

The preliminary double-differential invariant-mass-rapidity spectra of correlated $\pi^+p$ pairs after subtraction of the combinatorial background [13] is shown in Fig. 4. The spectra is dominated by the $\Delta(1232)$ resonance around 1150 MeV/c$^2$ being its mass strongly shifted down with respect to the vacuum due to kinematics. The multi-differential reconstruction of baryon resonances will allow to constraint better the models and clarify their connection to the structure and bulk properties of QCD matter formed in heavy-ion collisions.

3. Properties and dynamics of hot and dense matter
Recent theoretical studies demonstrate the sensitivity of the event-by-event net-baryon number distribution to the critical behaviour of QCD matter and to the presence of a critical endpoint. HADES can provide the lowest point in the excitation function and clarify the observed trends by the STAR Collaboration (see [15] and references therein). However, questions related to the influence of volume fluctuations related to finite centrality resolution or the effect of bound states such as deuterium and tritium and it impact on the proton number as proxy for baryon number.

Flow and particle correlations play a fundamental role in identifying properties and evolution of heavy-ion collisions. These measurements allow one to access information on the equation of state of dense nuclear matter and spatial and temporal information on the source size. The 3-dimensional femtoscopy analysis of identical pions has been performed [14] and its results are shown in Fig 5. For the first time a splitting between negative and positive pairs radii as a function of pair transverse momentum, $k_T$, has been observed due to interactions with the positively-charged medium as shown in the left panel of the figure. The excitation function of the
Figure 4. Left: Double differential invariant-mass spectra of $\pi^- p$ pairs as a function of rapidity after subtraction of the combinatorial background. Right: Same distribution for the $\pi^+ p$ pairs. The prominent structure around 1150 MeV/c$^2$ can be identified as the $\Delta(1232)$ resonance. The differences is the shape point to significant isospin-dependent effect related to the long evolving $\Delta \leftrightarrow \pi + N$ cycle present at these energies. The opposite behaviour at threshold mass is mainly due to long range Coulomb interaction.

Figure 5. Left: Source radii (invariant, out, side and long) obtained from fits to one and 3-D correlation functions of $\pi^+\pi^+$ (black squares) and $\pi^-\pi^-$ (red circles) as function of pair transverse momentum, $k_T$, for central (0-10 %) Au + Au collisions at 1.23A GeV. Blue dashed lines represent the constructed radii for neutral pion pairs. Error bars represent the statistical and the hatched bands represent the systematic errors, respectively. Right: Excitation function of the source radii $R_{out}$ (upper panel), $R_{side}$ (central panel), and $R_{long}$ (lower panel) for pairs of identical pions with transverse mass of $m_T = 260$ MeV in central collisions of Au + Au or Pb + Pb measured as LHC, RHIC, SPS, and AGS. Further details on the figures and references to data points can be found in [14].
obtained radii are shown over four order in magnitude in energy, being the region between 2 and 10 GeV subject of more detailed research and attention. The large data sample collected during the Au+Au run allows one to investigate the higher order flow coefficients [16], fundamental to increase the understanding of the properties of the hadronic medium.

4. Summary
HADES provides measurements at the lowest energy among running heavy-ion experiments. This permits to set the origin of excitation functions of production of particles or collective properties. Moreover, matter created at these energies recreates the properties of cosmic matter created in neutron-star mergers which might be the origin for the heavy elements in our Universe. Future experiments will planned to continue the scientific program at the FAIR Phase-0.

The HADES Collaboration acknowledges the support by LIP Coimbra (Portugal) PTDC/FIS/113339/2009, SIP JUC Cracow, Cracow (Poland), National Science Center, 2016/23/P/ST2/040 POLONEZ, 2017/25/N/ST2/00580, 2017/26/M/ST2/00600; TU Darmstadt, Darmstadt (Germany), VH-NG-823, DFG GRK 2128, DFG CRC-TR 211, BMBF:05P18RDFC1; Goethe-University, Frankfurt (Germany) and TU Darmstadt, Darmstadt (Germany), ExtreMe Matter Institute EMMI at GSI Darmstadt; TU München, Garching (Germany), MLL München, DFG ECUST 153, GSI TMLRG1316F, BmBF 05P15WOFCA, SFB 1258, DFG FAB898/2-2; NRNU MEPhI Moscow, Moscow (Russia), in framework of Russian Academic Excellence Project 02.a03.21.0005, Ministry of Science and Education of the Russian Federation 3.3380.2017/4.6; JLU Giessen, Giessen (Germany), BMBF:05P12RGGHM; IPN Orsay, Orsay Cedex (France), CNRS/IN2P3; NPI CAS, Rez, Rez (Czech Republic), MSMT LM2015049, OP VVV CZ.02.1.01/0.0/0.0/16 013/0001677, LTT17003.

References
[1] Most E R et al. 2019 Phys. Rev. Lett. 122 061101 (Preprint 1807.03684)
[2] Metzger B D et al. 2010 Mon. Not. Roy. Astron. Soc. 406 2650 (Preprint 1001.5029)
[3] Kasen D et al. 2017 Nature 551 80 (Preprint 1710.05463)
[4] Agakishiev G et al. (HADES) 2009 Eur. Phys. J. A 41 243 (Preprint 0902.3478)
[5] Adamczewski-Musch J et al. (HADES) 2018 Eur. Phys. J. A 54 85 (Preprint 1712.07993)
[6] Adamczewski-Musch J et al. (HADES) 2019 Nature Physics, 15 1040–1045
[7] Adamczewski-Musch J et al. (HADES) 2019 Phys. Lett. B 793 457 (Preprint 1812.07304)
[8] Adamczewski-Musch J et al. (HADES) 2018 Phys. Lett. B 778 403 (Preprint 1703.08418)
[9] Adamczewski-Musch J et al. (HADES) 2019 Phys. Rev. Lett. 123 022002 (Preprint 1812.03728)
[10] van Hees H and Rapp R 2005 Phys. Lett. B 606 59 (Preprint nucl-th/0407050)
[11] Rapp R, Chanfray G and Wambach J 1997 Nucl. Phys. A 617 472 (Preprint hep-ph/9702210)
[12] Steinheimer J and Bleicher M 2016 J. Phys. G 43 015104 (Preprint 1503.07305)
[13] Kornakov G and Galatyuk T 2018 Accepted in Eur. Phys. J. A (Preprint 1808.05466)
[14] Adamczewski-Musch J et al. (HADES) 2019 Phys. Lett. B 795 446 (Preprint 1811.06213)
[15] Adamczyk L et al. (STAR) 2014 Phys. Rev. Lett. 112 032302 (Preprint 1309.5681)
[16] Kardan B (HADES) 2019 Nucl. Phys. A 982 431 (Preprint 1809.07821)