The HADES Pion Beam Facility

Introduction

The quest for unraveling the origin of confinement and spontaneous breaking of chiral symmetry have been the driving force for hadron and nuclear matter physics over the last two decades. Both processes are responsible for the generation of mass of all hadronic matter around us [1]. The High Acceptance DiElectron Spectrometer (www-hades.gsi.de) has been designed and put into operation in 2003 to search for signatures of a (partial) restoration of chiral symmetry, then thought to be observable by measuring in-medium (shift of pole) masses of the vector mesons [2, 3]. Electromagnetic decays of the low-mass vector mesons, in particular the ρ meson, represent a formidable choice since they can decay exclusively into a pair of leptons. Hence, in-medium decays become observable by reconstructing the invariant mass of the lepton pairs recorded in the spectrometer.

During more than 20 years of research on the emissivity of strongly interacting matter formed in collisions of heavy ions, at energies ranging from $\sqrt{s}$ = 2.3 GeV up to a 2 TeV per N-N pair, radiation off the medium has been unambiguously identified [4, 5]. Using reconstructed four momentum vectors of lepton pairs respective spectral distributions have successfully been used as thermometer, barometer and chronometer of the evolving fireball [6, 7]. An excitation function of lepton pair production has also been measured at the RHIC for energies between $20.0 \leq \sqrt{s}$/GeV ≤ 200. With HADES, the emissivity of baryon dominated matter has been investigated at SIS18 energies 2.4 $\sqrt{s}$ < 3.2 GeV. In contrast to the results at high beam energies, where the radiation in the spectral region below the vector meson pole masses can essentially be explained as $\pi^+\pi^-$ annihilation in the s-channel, at low beam energies the radiation of the fireball is better understood as electromagnetic decays of baryonic resonances. Assuming a strict Vector Meson Dominance (VMD) theorem the spectral distribution of the virtual (time-like) photons reflects in both cases the in-medium properties of the intermediate ρ meson. It has been demonstrated, that the in-medium propagator of the ρ meson should be substantially modified by strong coupling of the meson to baryonic resonance-hole states [8].

An ideal experiment to further test this hypothesis is the measurement of exclusive reaction channels of type $\pi + N \rightarrow e^+e^- + N$ where such resonances are directly excited and decay into e^+e^- N final state. To accomplish this, the recently upgraded HADES spectrometer can now additionally be operated with tracked secondary pion beams. But the physics potential of this facility goes well beyond: the coupling of, for example, strange mesons to baryons is of great importance for the understanding of in-medium kaon properties and the role of the meson cloud in hadron structure. Last not least, π-induced particle production off nuclei provides ideal conditions to study medium effects on the meson in almost recoil-less kinematics.

The Pion Beam Facility at GSI

The combination of secondary pion beam available at GSI with the universal HADES detector represents a worldwide unique facility. The π^--beam is generated by a primary ^{14}N beam, provided by the SIS18 synchrotron, with an intensity close to the space-charge limit of 0.8–1.0 10^{11} ions/spill. The pions are then transported to the HADES target, located 33 m downstream of the production point by a beam-line composed of a lattice of 7 quadrupole and 2 dipole magnets, as shown in Figure 1. For pions with a central momentum (p_0) a transmission of about 56% with respect to the entrance solid angle is achieved. The transmission decreases gradually as the π-momenta depart from the central momentum, reaching zero for pion momenta of $p_0 \pm 6\%$. The transmission can be represented to first order by a Gaussian distribution with a variance of $\delta p/p_0 = 1.5\%$. The pion intensity distribution at the exit of the pion beam-line (last quadrupole) depends on the selected p_0, reaching a maximum of about 10^6 pions/spill at p_0 = 1.0 GeV/c and decreasing to about half of this value at p = 0.7 GeV/c and 1.3 GeV/c. These intensities are the result of the combined effect of the beam size at production target and of the transmission, mostly driven by the dedicated tuning of the different magnets and the respective apertures defined by the vacuum vessels. For a beam of negative pions, the purity is high and the small contamination by electrons and muons has been estimated to be lower than a few %. Together with their low interaction probability this contamination does not constitute a handicap for the experiment.

A dedicated tracking system (CERBEROS), composed of two silicon strip-detectors along the pion chicane and a start detector right in front of the HADES spectrometer, has been developed and successfully commissioned to measure the momentum of each beam particle. The first silicon detector station (DET1 in Figure 1) is located close to the intermediate focus to minimize the effect of multiple

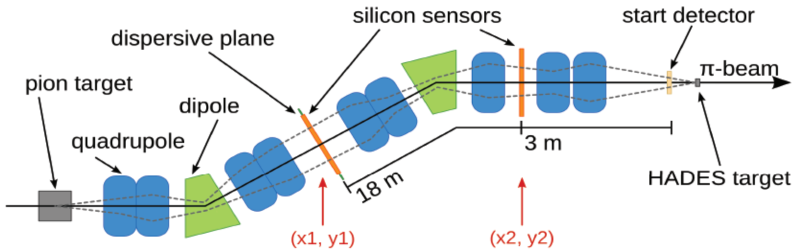


Figure 1. *Layout of the HADES pion beam-line with indicated positions of the pion production target, HADES target position, quadrupoles dipoles, and in-beam tracking detectors (indicated by arrows, DET1, DET2). Sketch of the beam optics. Note that the second dipole has reverse bias in this notation.*

scattering, the second one (DET2) is installed in the HADES cave close to the target. While DET1 is mostly sensitive to the momentum offset, DET2 provides additional spatial information to determine the three components of the pion momentum-vector at the HADES target point. Each of the 0.3 mm thick, double-sided silicon detectors cover an area of 10×10 cm^2 and are segmented into 128 strips oriented vertically (Y) and horizontally (X). From the measured positions of the hit on the two detectors, the pion momentum is reconstructed with a resolution ranging from 0.1% to 0.3% over the acceptance window. This allows for a precise reconstruction of the total center-of-mass energy in pion-nucleon interactions. The detector is read-out by an ASIC, n-XYTER [9], providing as well time as amplitude information, connected to the HADES Trigger and Read-out Board. During the first round of experiments the detectors operated stably in the harsh environment due to a high background level close to the production target (more than 1 MHz on DET1).

Calculations of the pion beam optics have shown that the beam spot at the HADES target position exceeds the diameter of the target (12 mm) and can cause significant background from beam interactions in the narrow RICH beam tube or target holder. In order to reject this background and to also provide start time information a position sensitive detector was placed at 30 cm in front of the HADES target. This detector consists of two layers, each of them composed of four, 0.3 mm thick mono-crystalline diamond wafers (4.7×4.7 mm^2). This detector provides excellent time resolution ($\sigma = 100$ ps), an efficiency close to 100% for minimum ionising pions and very high rate capability of $<10^7$ hits/cm^2.

The HADES detector has been recently upgraded to provide uniform granularity and improved rate capability. The detector consists (Figure 2, left) of a hadron blind ($\gamma_{threshold} = 18.1$) gaseous Ring-Imaging Cherenkov (RICH) detector, four planes of Mini-Drift Chambers for track reconstruction and a Time-Of-Flight wall based on scintillators-TOF- (for polar angles $\vartheta > 45°$) and Resistive Plate Counters RPC (for $\vartheta < 45°$) supplemented at forward polar angles with Pre-SHOWER chambers for electron shower measurement. The detector features an excellent invariant mass resolution of $\Delta M/M_{e+e-} \cong 2.5\%$ at the ρ/ω mass poles and electron/hadron separation (better than 10^{-5}). With the addition of the RPC in 2010 HADES provides now an excellent time-of-flight resolution in the full acceptance of $\sigma = 120$ ps and $\sigma = 80$ ps for the TOF and RPC systems, respectively. In combination with the 2–3% momentum resolution of the tracking system the proton/pion and kaon/pion separation (3 σ) reaches up to 1.8 GeV/c and ~1.2 GeV/c, respectively (Figure 2, right).

Performance Results from First Experiments with Pion Beam

The new facility has been operated in 2014 to take data for π^- induced reaction in two runs with in total two weeks beam on target. Run 1 was dedicated to strangeness production

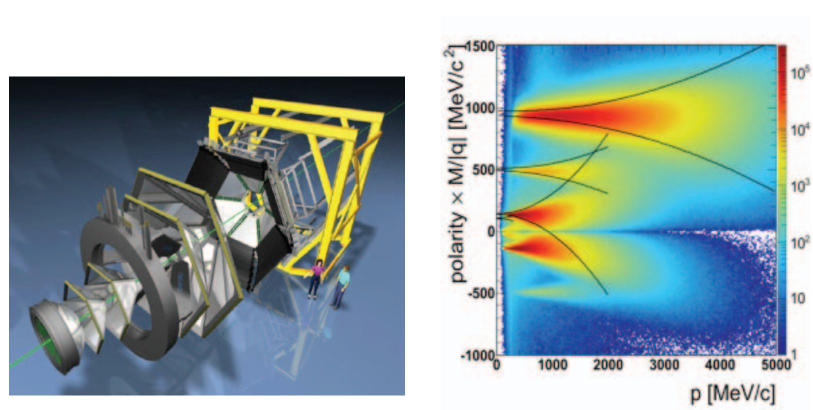
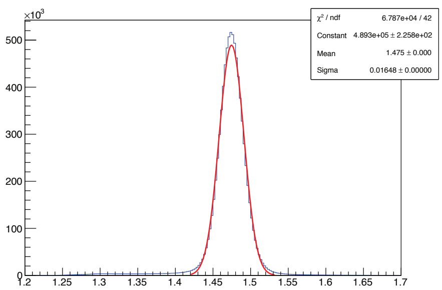


Figure 2. *Left: Artist view of the HADES detector. Six identical sectors cover the full azimuth. The beam location is indicated by the green straight. For measurements, the detectors are pulled tightly to the magnet. Right: Mass of particles deduced from the time-of-flight and the momentum measurements versus the momentum for particles produced in central Au + Au collisions at 4 AGeV (simulations based on the measured detector performance).*



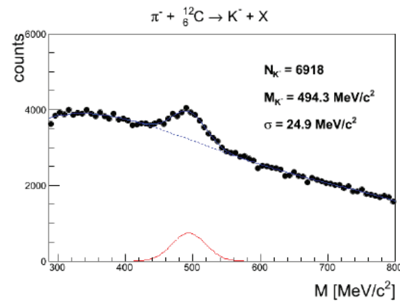


Figure 3. *Left: $p^-\pi^-$ Invariant mass distribution from selected π + p elastic collisions. Right: Reconstructed K^- mass in π^- + C reactions.*

in π^- induced reactions on a heavy and light nuclei (C/W) at a beam momentum of p_0 = 1.7 GeV/c. The collected data will allow to study the in medium kaon potential as well as the ϕ and antikaon meson absorption in cold nuclear matter. In a more general perspective, such experiments will provide new insight in particle production in scattering, charge exchange or absorption reactions. The goal of run 2 was to measure the excitation function of two-pion production in the π^--p reactions around the pole of D_{13}(1520) resonance. The exclusive two pion production data will be analyzed with the partial wave technique to disentangle the different waves that build up coherently the measured final state and will provide a production amplitude of the ρ meson production in the second resonance region. This information will be used to understand quantitatively how the off-shell ρ meson decay into e^+e^- pairs enters in the total dilepton production measured simultaneously in this run. This long awaited result is important for the understanding of the applicability of VDM to baryons and the broadening of the ρ meson observed in proton-nucleus (HADES) and heavy ion reactions discussed in the introduction.

Figure 3 (left) shows the distribution of total CMS energy reconstructed from π + p elastic scattering, selected by angular correlations, indicating no significant background from non-target interactions and a width that is dominated by the HADES momentum resolution (σ_{CMS} = 1.2%). The recorded statistics for two-pion production ($\pi^+\pi^-$ and $\pi^-\pi^0$) exceeds the existing data base by about two orders of magnitude. The right panel of Figure 3 shows the reconstructed on-line mass of K^- produced in π^- + C reactions for a central beam momentum of 1.7 GeV/c. This preliminary result already demonstrates the high purity of the K^- selection which will allow studying K^- production on nuclei of increasing mass size with unprecedented precision.

Outlook

It is expected that the HADES pion beam program will be continued in 2017 after the SIS18 has been upgraded to serve as injector for the FAIR facility. For 2016 the HADES collaboration plans to complement the detector by a large area electromagnetic calorimeter (ECAL). The ECAL for HADES will be built from 978 lead glass modules and will replace the Pre-Shower detector. The calorimeter will enable measurements of real photons emitted from nuclear matter, neutral meson production via their photonic decays (for example, $\eta/\pi \rightarrow \gamma\gamma$), and further improve electron identification. The latter is crucial for the operation at higher energies available at SIS100 of FAIR. For π^--N reactions the reconstruction of neutral mesons is essential to complete the database for partial wave analysis (PWA). Furthermore, a concept is developed to operate the RICH UV-photon detector based on multi-anode photo multipliers instead of the existing Multiwire Proportional Chambers with CsI photocathodes. The latter project is a synergy between the HADES and the CBM RICH construction.

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