REFEREE REPORT
on the project HADES (JINR participation) in 2022-2024
(Theme 02-1-1106-2011/2022)

The experimental investigations of properties of nuclear matter produced in heavy ion collisions over a wide range of energy and centrality of collision studied with various probes is in the center of nuclear programs performed at LHC and SPS at CERN, RHIC at BNL, and SIS-18 at GSI. The study of phase diagram of nuclear matter and determination of its features should shed light on our understanding fundamental properties of Nature and contribute to the development of modern theory of strong interactions, phase transition and critical phenomena.

The HADES detector is a large acceptance magnetic spectrometer operating with proton, deuteron and heavy ion beams extracted from the SIS-18 at GSI (Darmstadt).

The main experimental goal is to investigate properties of dense nuclear matter created in heavy ion collisions and ultimately learn about modification of hadron properties in medium. A precise spectroscopy of e+e− pairs and charged hadrons produced in proton, pion and heavy ion induced reactions in a 1.0-4.5 GeV kinetic beam energy region is of main achievement of the HADES facility.

The spectrometer features a sophisticated superconducting toroid, low-mass drift chambers (MDC), a ring-imaging Cherenkov detector (RICH) and lead-glass electromagnetic calorimeter (ECAL). The time-of-flight system (ToF) uses diamond start detectors and scintillator and resistive plate-based stop detectors. A tracking system consists of a set of 6 superconducting coils producing a toroidal field and drift chambers and a multiplicity and electron trigger array for additional electron-hadron discrimination and event characterization. A two-stage trigger system enhances events containing electrons. Identification of pions, kaons, and protons is achieved combining time-of-flight and energy loss measurements over a large momentum range. The Forward Wall (FW) is used for the measurements of the spectator protons and reaction plane determination for heavy-ion and deuteron-proton collisions studies.

The HADES research covers the processes of interaction between protons and pions with protons and nuclei, which are used as the reference for the selection of the actual nuclear effects of the environment. The design and features of the detector (high acceptance ~50%, high mass resolution ~ 2.5%) are focused on the registration of electron - positron pairs as the main probe in the study of the properties of vector mesons (ρ,ω) formed in the nuclear matter and their characteristics (mass, width) modification in this environment. The strange hadrons (kaons, hyperons) are also used as probes of nuclear matter studied in the experiment.

The physics program of HADES experiment is highly motivated. It includes the investigation of in-medium modification of light vector mesons, dilepton continuum in the warm and dense hadronic matter, production of the strange, multi-strange particles and hypernuclei as well.

Obtaining statistically provided and accurate information about the properties and characteristics of particles and the processes of their formation is necessary to search for and study features of phase transitions of nuclear matter, understanding the mechanism of restoration of chiral symmetry, finding the equation of state, and the phase diagram of

nuclear matter.

The main contribution of the JINR group to the HADES project is one of the 4 planes of drift chambers consisting of 6 modules, as well as the readout electronics for the chambers. All components are designed, developed, integrated into the system of the spectrometer and they work normally. The original mathematical software for the search and reconstruction of tracks in the system of drift chambers of the HADES spectrometer is developed. JINR group take part in data analysis on the study on the study of the yields of charged pions and dileptons in π+p, n+p and p+p collisions.

The Project describes the JINR contribution in the HADES detector.

A tracking system of HADES consists of a set of 6 superconducting coils producing a toroidal field and 4 planes of multi-wire drift chambers (MWDCs). The JINR physicists were responsible for the design, production, and maintenance of the 2-nd plane of low mass multi-wire drift chambers. The FEE electronics for drift chambers has been developed also at JINR. JINR physicists developed tracking software for the momentum and vertex reconstruction and participated in the development of the alignment procedure for HADES. The JINR group provided technical support for the second plane of the drift chambers during data taking for Ag+Ag collisions in 2019, and fully restored the operability of the second plane of the drift chambers of the setup after the run.

The major HADES upgrades there were the installation of new RICH, the lead-glass electromagnetic calorimeter (ECAL), new diamond start detector and modernized DAQ system.

In future HADES will be a part of the CBM (Compressed Baryonic Matter) experiment at the Facility for Antiproton and Ion Research (FAIR). The spectrometer after upgrade will be able to study nuclear reactions in the energy range from 2 to 10 GeV/nucleon.

We would like to note some interesting recent experimental results from HADES.

The measured emission of e+e− pairs from C+C collisions at an incident energy of 1 AGeV display a strong excess above the cocktail of standard hadronic sources (6.3. times).

The invariant-mass spectrum of e+e− pairs produced in C+C collisions at an incident energy of 2 AGeV also demonstrates the excess by 2 times in the M_{ee} range of 0.15-0.6 GeV/c^2.

The detailed studies of the origin of the DLS «puzzle» motivated the measurements of electron pair production in elementary p+p and d+p reactions at 1.25 GeV/nucleon.

For the first time, the electron pairs were reconstructed for n+p reactions by detecting the proton spectator from the deuteron breakup by Forward Wall. It was found that the yield of electron pairs with invariant mass $M_{ee} > 0.15$ GeV/c^2 is about an order of magnitude larger in n+p reactions as compared to p+p.

For the first time sub-threshould ω mesons were reconstructed in a heavy-ion Ar+KCl collisions at 1.76 AGeV.

At intermediate e+e− invariant masses, a strong enhancement of the pair yield over a reference spectrum from elementary nucleon-nucleon reactions was found.

HBT correlations with high-statistics $\pi-\pi-$ and $\pi+\pi+$ data for Au + Au collisions at 1.23 AGeV were studied.

Flow coefficients v_n of the orders n=1–6 measured for protons, deuterons, and tritons as a function of centrality, transverse momentum, and rapidity in Au+Au collisions at 1.23 AGeV were also studied and can be used in constraining the equation of state of dense

baryonic matter.

First results on the sub-threshould neutral kaons and lambda-hyperons in Au+Au at 1.23A GeV have been obtained.

The physical results obtained by the collaboration are regularly presented at international conferences and published in refereed journals.

In 2022-2024 the HADES collaboration plans to perform measurements on beams of protons, deuterons, gold, and secondary pions at the SIS-18 accelerator.

JINR group will participate in the preparation and technical support during the beam time of the plane 2 of MWDCs, the software support during data taking and DST production. JINR group is planning to take a part in the analysis of the p+p data at 4.5 GeV. The major goal is to study di-electron and hadronic observables. The JINR group is traditionally involved in the studies of the hadronic probes in elementary reactions. The physics includes multi-pion production in different reactions and their azimuthal correlations. The theoretical interpretation of HADES data will be also continued.

In the future, it is planned to continue research at the SIS-100 accelerator complex in the energy range of 3-10 AGeV nuclei. JINR group will participate in HADES upgrade program and physics simulation for SIS100. The MWDC upgrade includes new FEE program and software development for tracking in MWDC and Forward Detector, RICH. JINR group is planning to make a second stand on the FEE for MWDC at VBLHEP.

Resources requested by the authors for the implementation of work on the HADES project (JINR participation) in 2022-2024 justified. I believe that the work on the project should be continued with the first priority and the Project should be submitted for consideration by the JINR PAC.

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