MPD Detector at NICA

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Abstract: The goal of this article is to give information about the new accelerator complex NICA at JINR, Dubna and especially, to provide overview of the MultiPurpose Detector (MPD) and its subdetectors. The current results of the MPD performance for dileptons, hyperons, hypernuclei and \( \phi \)-meson are presented.

The Nuclotron-based Ion Collider fAcility (NICA), shown in figure 1, is a new accelerator complex being constructed at JINR, Dubna, Russia. The global scientific goal of the NICA/MPD project is to explore the phase diagram of strongly interacting matter in the region of highly compressed baryonic matter. The study of hot and dense baryonic matter provides relevant information on the in-medium properties of hadrons and nuclear matter equation of state; allows a search for deconfinement and/or chiral symmetry restoration, phase transition, mixed phase and critical end-point, possible strong P- and CP violation; gives information about the evolution of the Early Universe and the formation of neutron stars. [1]

Figure 1. NICA accelerator complex at JINR  
Figure 2. General view of the MPD detector

NICA's aim is to provide collisions of heavy ions over a wide range of atomic masses, from Au+Au collisions at \( \sqrt{s_{NN}} = 11 \text{ GeV} \) (for Au\(^{197}\)) and an average luminosity of \( L = 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \) to proton-proton collisions with \( \sqrt{s_{pp}} = 20 \text{ GeV} \) and \( L \approx 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \). Two interaction points are foreseen at NICA which provide a possibility for two detectors to operate simultaneously - MultiPurpose Detector (MPD) and Spin Physics Detector (SPD). This overview is focused on the MPD detector.

The MPD experimental program includes simultaneous measurements of observables that are presumably sensitive to high nuclear density effects and phase transitions. In the first stage of the project (starting in 2017) are considered - multiplicity and spectral characteristics of the identified hadrons including strange particles, multi-strange baryons and antibaryons; event-by-event fluctuations in multiplicity, charges and transverse momentum; collective flows (directed, elliptic and higher ones) for observed hadrons. In the second stage (starting in 2020) the electromagnetic probes (photons and dileptons) will be measured. It is proposed that along with heavy ions NICA will provide proton and light ion beams including the possibility to use polarized beams.
The software framework for the MPD experiment (MpdRoot) is based on FairRoot and provides a powerful tool for detector performance studies, development of algorithms for reconstruction and physics analysis of the data. [2] Extended set of event generators for heavy ion collisions is used (UrQMD, LAQGSM, HSD). [3]

The detector for exploring phase diagram of strongly interacting matter in a high track multiplicity environment has to cover a large phase space, be functional at high interaction rates and comprise high efficiency and excellent particle identification capabilities. The MPD detector, shown in figure 2, matches all these requirements. It consists of central detector (CD) and two optional forward spectrometers (FS-A and FS-B). CD consists of a barrel part and two end caps. The barrel part is a set of various subdetectors. The main tracker is the time projection chamber (TPC) supplemented by the inner tracker (IT). IT and TPC have to provide precise tracking, momentum determination and vertex reconstruction. The time of flight (TOF) system must be able to identify charged hadrons and nuclear clusters in a broad pseudorapidity range. The electromagnetic calorimeter (ECAL) should identify electrons, photons and measure their energy with high precision. The zero degree calorimeter (ZDC) should provide event centrality and event plane determination, and also measurement of the energy deposited by spectators. There are also a straw-tube tracker (ECT) and a fast forward detector (FFD).

The magnet of MPD is a solenoid with a thin superconducting NbTi winding and a flux return iron yoke. The magnet should provide a homogeneous magnetic field of 0.5 T. The field inhomogeneity in the tracker area of the detector is about 0.1%.

The MPD time projection chamber (TPC) is the main tracking detector of the central barrel and has to provide charged particles momentum measurement with sufficient resolution (about 2% at \( p_t = 300 \) MeV/c), particle identification and vertex determination, two track separation (with a resolution <1 cm) and dE/dx measurement (dE/dx resolution better than 8%) for hadronic and leptonic observables at pseudorapidities \( \eta < 2.0 \) and \( p_t > 100 \) MeV/c. TPC readout system is based on Multi-Wire Proportional Chambers (MWPC) with cathode readout pads.

The inner tracker system (ITS) should enhance track reconstruction. ITS is able to restore tracks of particles with momentum less than 100 MeV/c and provides precise primary and secondary vertexes reconstruction with an accuracy of ~ 40 μm. ITS should also identify relatively rare events with production of hyperons. ITS is based on the Silicon Strip Detector (SSD) technology. It consists of a silicon barrel and discs which will register particles with large pseudorapidity \( \vert \eta \vert < 2.5 \).

The identification of charged hadrons (PID) at intermediate momentum (0.1–3 GeV/c) is achieved by the time-of-flight (TOF) measurements which are complemented by the energy loss (dE/dx) information from the TPC and IT detector systems. TOF system should provide a large phase space coverage \( \vert \eta \vert < 3.0 \), high combined geometrical and detection efficiency (better than 80%), identification of pions and kaons with \( 0.1 < p_t < 2 \) GeV/c and (anti)protons with \( 0.3 < p_t < 3 \) GeV/c. The choice for the TOF system is Multigap Resistive Plate Counters (MRPC) which have good time resolution of \( \sigma < 70 \) ps. The barrel covers the pseudorapidity region \( \vert \eta \vert < 1.5 \) and the geometry efficiency in it is above 90%. The end cap system covers the pseudorapidity region \( 1.5 \leq \vert \eta \vert < 3.0 \).

The fast forward detector (FFD) should provide fast determination of a nucleus-nucleus interaction in the center of MPD, generation of a start pulse for TOF and production of L0-trigger signal. The proposed FFD design is a granulated Cherenkov detector which has a high efficiency for the high energy photons and for ultra-relativistic charged particles as well. Its acceptance in pseudorapidity is \( 2.0 \leq \vert \eta \vert \leq 4.0 \). FFD has excellent time resolution of 38 ps.

The end cap tracker (ECT) has to provide charged particle identification and momentum measurement in the pseudorapidities \( 1 < \vert \eta \vert < 2.2 \). ECT has high track reconstruction efficiency and momentum resolution about 10%. ECT consists of two end cap parts which are made with modules, containing layers of straw tubes.

The primary role of the electromagnetic calorimeter (ECAL) is to measure the spatial position and energy of electrons and photons. ECAL should have a high segmentation, should provide good space resolution, energy resolution about 3% and should allow a separation of overlapping showers. The Pb-scintillator ECAL of the “shashlyk” type will be used.
The zero degree calorimeter (ZDC) should provide a classification of events by centrality, event plane determination and measurement of the energy deposited by spectators. ZDC consists of modules of 60 lead-scintillator tile “sandwiches” with lead and scintillator plates. The light readout is provided by the wave-length shifting fibers (WLS-fibers) and the micropixel avalanche photodiodes (MAPDs).

More detailed description of the MPD detector can be found in 'MPD Conceptual Design Report'. [1]

Measurements of the production of strange particles such as the φ-meson can provide important information on the properties of the medium and particle production mechanisms in ultra-relativistic Au-Au collisions. Measurements of the φ-meson p_T spectra and their dependence in terms of shape and normalization on centrality may shed light on the constituents of the medium at the time of φ formation as well as the mechanism through which the φ-mesons are formed. Further insight into mechanisms of particle production for strange particles compared to non-strange particles can be gained through measurement of the particle ratios of multistrange hadrons. The medium produced at NICA/MPD can be also probed by measuring the elliptic flow of the φ-meson. Since multistrange hadrons and particles with hidden strangeness are assumed to freeze out early and undergo fewer interactions in the hadronic stage, their v_2 signals should provide a clean signal from the early stage of the system’s evolution. [4] The φ vector meson is the lightest bound state of hidden strangeness, consisting of a quark-antiquark pair. Although it is a meson, it is heavy in comparison with mesons consisting of u and d quarks, having a mass (m_φ = 1019.456 ± 0.020 MeV/c^2) comparable to the proton and Λ baryons. The φ-meson is expected to have a very small cross-section for interactions with non-strange hadrons. [4] [5] It is unstable and its existence can only be detected by its decay products such as K+K−, K_L^0 K_S^0, μ+μ−, etc.

In our study we use the channel decay Φ→K+K− to detect the formation of the φ-meson. This channel is chosen because it has a high branching ratio (49.1%) and kaons are easy to detect. UrQMD event generator is used and central events at √s = 11 GeV are analyzed. In the analysis is used selection of kaon pairs by track quality cuts and particle identification (PID). The invariant mass of the kaon pairs is calculated and then the combinatorial background (mixed-event technique) is subtracted. The obtained peak from the invariant mass distribution is then fitted by a Breit-Wigner function and the characteristics of the φ-meson such as its mass and its width are found. The recent results of the φ-meson study are shown in figure 3. The values of the parameters obtained by the fit (Width = 4.291 ± 0.104 MeV/c^2 and M_inv = 1019.995 ± 0.022 MeV/c^2) are consistent with the values given in literature. This study shows that the measurement of φ-mesons is feasible and we can expect detection of them when NICA/MPD will be put in operation.

The correlated e^+e^− or μ^+μ^− pairs (dileptons), especially those from decays of vector mesons (ρ, ω, φ), are the best candidates to relate medium modifications of hadronic spectral function to the
restoration of the chiral symmetry in A+A collisions. The invariant mass distribution of electron-positron pair reflects the mass distribution of the vector meson at the moment of the decay and since the decay products interact only electromagnetically, they escape the interaction region unaffected by subsequent strong interactions in dense hadronic matter and carry to the detectors information about the conditions and properties of the medium at the time of their creation.

The experimental study of dileptons in heavy-ion collisions is a challenging task. The main difficulty is a huge combinatorial background of uncorrelated lepton pairs which mainly come from π0 Dalitz decays and photon conversion in the detector material. A special attention should be paid to reduce this background as much as possible. The configuration used in the study includes TPC, TOF and ECAL covering the pseudorapidity range |η| < 1.2.

The study of dielectron production in central (0-3 fm) Au-Au collisions at √s = 7A GeV was performed using the Pluto code [6] generating a cocktail of hadrons decaying into the electron-positron or Dalitz electron-positron pairs. The multiplicities of dilepton sources (π0, η, ρ0, ω, φ) were predicted by the statistical thermal model [7]. The background was calculated by the UrQMD generator [8] which produced hadrons and photons, and mixed with the Pluto output. The event samples have been transported through the detector using the Geant 3.21 transport package (containing photon conversions, etc.). Then the events were reconstructed and analysed [9].

Figure 4 shows the signal-to-background ratio (S/B) in invariant mass bins of 20 MeV/c^2 obtained for 2x10^7 central events, corresponding to about 20 hours of running time at the NICA collision rate of 6 kHz. The signal-to-background ratio is defined as the ratio of the number of e^+e^- combinations from meson decays to that of all the other electron-positron combinations. The obtained results for the signal-to-background ratio in the invariant mass interval 0.2-1.5 GeV/c^2 are shown in figure 5 along with the published data from other experiments.

One of the main tasks of the NICA/MPD physics program is a study of the strangeness production (hyperons and hypernuclei) in heavy ion collisions. Since hyperons are created during the early stages of the fireball evolution, they could provide essential signatures of the excited and compressed baryonic matter. The heaviest species, multistrange Ξ− and Ω−, are especially interesting for physics analyses. Their identification and reconstruction is based on the reconstruction of the lightest hyperon Λ0. In addition, since Λ0 hyperons are produced in relatively large quantities and have very attractive experimental features (resonance structure and simple decay mode), they can be used as a tool to study the detector performance. Therefore, the development of the Λ0 reconstruction techniques is a very important task.

The production of hypernuclei in relativistic heavy ion collisions is also interesting for understanding the strangeness degrees of freedom in hadronic systems. The study of the production of the light hypernuclei 3ΛH is essential for understanding the production mechanism of exotic objects such as multi-hypernuclei and the strangelets they might decay into if the latter are more
stable. The coalescence process for the formation of hypernuclei requires that nucleons and hyperons be in proximity in phase space (i.e., in coordinate and momentum space). Equilibration among the strange quark flavors and light quark flavors is one of the proposed signatures of QGP formation, which would result in high hypernucleus yields.

The detector configuration used in the study includes TPC and TOF for track reconstruction and particle identification in the pseudorapidity range $|\eta| < 1.3$. The gold-gold collisions were generated using the LAQGSM code [11]. $\Lambda^0$ hyperons and $^3\Lambda^0 H$ hypernuclei were reconstructed using their decay mode into a negative pion and a proton (for hyperon) or $^3\text{He}$ (for hypernuclei). The signal event topology (decay of a relatively long-lived particle into a pair of charged tracks) defines the selection criteria: relatively large distance of the closest approach (DCA) to the primary vertex of decay products, small two-track separation in the decay vertex, relatively large decay length of the mother particle. The exact values of selection cuts were found by performing a multidimensional scan over the whole set of selection criteria with a requirement to maximize the invariant mass peak significance, defined as $S/\sqrt{S+B}$ where $S$ and $B$ are total numbers of signal (described by the gaussian) and background (polynomial function) combinations inside $+\, -\, 2\sigma$ interval around the peak position. The obtained results are presented in figure 6 and figure 7 where invariant mass distributions are plotted. One can see that MPD can do a good job in reconstructing strange objects.

![Invariant mass: $\Lambda \rightarrow p + \pi^-$ in central Au+Au collisions at 5A GeV obtained for $10^4$ events (30 seconds of running time).](image1)

![Invariant mass: $^3\Lambda^0 H \rightarrow ^3\text{He} + \pi^-$ in central Au+Au collisions at 5A GeV obtained for $5\times10^5$ events (30 minutes of running time).](image2)

In conclusion, it should be said that the MPD detector has many advantages and meets all the ambitious physics requirements for exploring phase diagram of strongly interacting matter in a high track multiplicity environment. The MPD detector's advantages comprise coverage of a large phase space, functionality at high interaction rates, high efficiency and excellent particle identification capabilities. The study of hyperons, hypernuclei, dileptons and vector mesons such as the $\phi$-meson, based on the current analyses, is feasible and gives quite good results. Therefore, NICA facilities provide unique capabilities for studying fundamental properties of the theory of strong interactions.

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