The CBM ECAL

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Abstract. We present the design and performance of the Electromagnetic Calorimeter (ECAL) of the Compressed Baryonic Matter (CBM) Experiment at FAIR. The main purpose of the ECAL detector is the identification and the measurement of energy and position of photons and electrons, which are produced in high-energy heavy-ion collisions in the beam energy range from 4 to 40 AGeV. ECAL will measure spectra of photons and neutral mesons decaying in their photonic decay channels. Precise measurement of masses and widths of short-living mesons ($\omega$, $\eta$, $\eta'$, $\phi$, $\chi_c$ etc.) will shed light on the chiral symmetry restoration which is expected to occur in dense nuclear matter. Measurements of the $\pi^0$ and $\eta$ meson spectrum are important to study dependence of the particle yield on thermodynamical parameters of nuclear matter.

1. Introduction

Substantial experimental and theoretical efforts worldwide are devoted to the exploration of the phase diagram of nuclear matter. Cold nuclear matter — as found in normal nuclei with a net-baryon density equal to one — consists of protons and neutrons only. At moderate temperatures and densities, nucleons are excited to short-lived states which decay by emission of mesons. At higher temperatures, also baryon-antibaryon pairs are created. This mixture of baryons, antibaryons and mesons, all strongly interacting particles, is generally called hadronic matter. At very high temperatures or densities the hadrons melt, and the constituents, the quarks and gluons, form a new phase: the Quark-Gluon-Plasma. For very low net-baryon densities where the numbers of particles and anti-particles are approximately equal, theory predicts that hadrons dissolve into quarks and gluons above a temperature of about 160 MeV \cite{1, 2}. The inverse process happened in the universe during the first few microseconds after the big bang: the quarks and gluons were confined into hadrons. In this region of the phase diagram the transition is expected to be a smooth crossover from partonic to hadronic matter \cite{3}. Calculations suggest a critical endpoint at relatively large values of the baryon chemical potential \cite{4}. Beyond this critical endpoint, for larger values of net-baryon densities (and for lower temperatures), one expects a phase transition from hadronic to partonic matter with a phase coexistence region in between. A new phase of so called quarkyonic matter has been proposed to exist beyond the first order phase transition at large baryon chemical potentials and moderate temperatures \cite{5}.

High density but cold nuclear matter is expected to exist in the core of neutron stars, and at very high densities correlated quark-quark pairs are predicted to form a color superconductor. In the laboratory hot and dense nuclear matter is generated in a wide range of temperatures and densities by colliding atomic nuclei at high energies. The goal of the experiments at RHIC and LHC is to investigate the properties of deconfined QCD matter at very high temperatures and
almost zero net-baryon densities. Several experimental programs are devoted to the exploration of the QCD phase diagram at high net-baryon densities. The STAR collaboration at RHIC scanned the beam energies in order to search for the QCD critical endpoint [6]. For the same reason, measurements are performed at the CERN-SPS with the upgraded NA49 detector (NA61) using light and medium size ion beams [7].

At the Joint Institute for Nuclear Research (JINR) in Dubna, a heavy-ion collider project (NICA) is planned with the goal to search for the coexistence phase of nuclear matter [8]. However, due to luminosity or detector limitations these experiments are constrained to the investigation of particles which are abundantly produced. In contrast, the Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt is designed for precision measurements of multidimensional observables including particles with very low production cross sections using the high-intensity heavy-ion beams provided by the FAIR accelerators.

Figure 1. The CBM experimental facility with the electron detectors.

The CBM experimental strategy is to perform systematic both integral and differential measurements of almost all the particles produced in nuclear collisions (i.e. yields, phase-space distributions, correlations and fluctuations) with unprecedented precision and statistics. These measurements will be performed in nucleus-nucleus, proton-nucleus, and — for baseline determination — proton-proton collisions at different beam energies. The identification of multistrange hyperons, hypernuclei, particles with charm quarks and vector mesons decaying into lepton pairs requires efficient background suppression and very high interaction rates. In order to select events containing those rare observables, the tracks of each collision have to be reconstructed and filtered on-line with respect to physical signatures. This concept represents a paradigm shift for data taking in high-energy physics experiments: CBM will run without
hierarchical trigger system. Self-triggered readout electronics, a high-speed data processing and acquisition system, fast algorithms, and, last but not least, radiation hard detectors are required for a successful operation of the experiment. Figure 1 depicts the CBM experimental setup with electron detectors (muon detection system is moved out from the acceptance).

2. The CBM electromagnetic calorimeter

The main purpose of the electromagnetic calorimeter (ECAL) in the CBM experiment is to identify electrons and photons and to provide measurements of their energy and position. ECAL will measure spectra of photons and neutral mesons decaying in their photonic decay channels. Precise measurement of masses and widths of short-living mesons ($\omega, \eta, \eta', \phi, f_2(1270), \chi_c$ etc.) will shed light on the chiral symmetry restoration which is expected to occur in dense nuclear matter. Measurement of the $\pi^0$ spectrum is important to study dependence of the particle yield on thermodynamical parameters of nuclear matter. Gluon-rich environment at high densities may produce gluonic bound states, referred to as glueballs, which can be observed in the two-photon decay mode. Elliptic and directed flows of $\pi^0$ measured by ECAL will be used for the collision geometry and collective phenomena studies. Having been used together with RICH and TRD, ECAL will significantly contribute to the particle identification due to its high capability to discriminate photons, electrons and hadrons with high efficiency and purity and will allow considerably improve the $J/\psi$ identification.

![Figure 2. Optimized for SIS100 CBM calorimeter system.](image)

The CBM electromagnetic calorimeter (ECAL) uses the “shashlik” technology, proved with several large detector systems in HERA-B, PHENIX and LHCb detectors [9, 10, 11]. It is built from individual modules that are made from lead absorber plates interspaced with scintillator tiles as active material. Wavelength-shifting (WLS) fibers penetrate the lead/scintillator stack through holes, and readout at the back of sampling structure by photomultipliers. Initially we were proposing large calorimeter system (at 12 m from the target) covering the full CBM angular acceptance and consisting of 3 different module types innermost section built with $40 \times 40 \text{ mm}^2$ cells, middle section built with $60 \times 60 \text{ mm}^2$ cells and outer section built with $120 \times 120 \text{ mm}^2$ cells. Total number of channels in this setup was about 24000. Due to the very high price the collaboration has not supported the full acceptance calorimeter. Optimized for SIS100
Figure 3. Invariant mass distributions of reconstructed photon pairs after background subtraction at $\pi^0$ mass region (left) and reconstructed photon pairs from MC-truth $\eta$-mesons (right).

calorimeter system has only 4352 electronic channels, built from 1088 modules of only one type (with $60 \times 60$ mm$^2$ cells). Calorimeter modules are grouped in two rectangular blocks which could be moved up and down (changing the angular range of measured particles and optimizing the experimental conditions for different colliding ion systems and beam energies) as illustrated on figure 2.

Recent year’s developments of the “shashlik” technology [12, 13, 14] have shown that electromagnetic shower energies can be measured with resolution of $\sigma(E)/E = 5%/\sqrt{E} \oplus 1.2\%$ (E in GeV), which provides sufficient electron/hadron separation. This performance is obtained using a sampling structure of 1.5 mm lead sheets interspersed with 2 mm thick scintillator plates, and a careful design of the light collection by the wavelength shifting fibers. Rather large amount of light produced in the calorimeter modules makes it possible to use conventional PMs for the calorimeter readout. Custom photomultipliers have demonstrated perfect performance with shashlik calorimeters during the last 20 years. The HV supply system in CBM electromagnetic calorimeter has to provide stable PM operation at high particle rates up to 10 MHz. A Cockroft-Walton base solution has shown very stable behavior in the HERA-B [9] and LHCb [11] calorimeters.

Performance of the CBM ECAL was checked with $\pi^0$ and $\eta$ mesons reconstruction for most difficult events – central Au+Au collisions at 10 AGeV. $1.5 \times 10^6$ UrQMD events were used. The invariant mass of all reconstructed photon pairs in each event was calculated and histogrammed. The shape of the background was estimated using “superevent” technique. The invariant mass for background was constructed using photons from different events. Number of pairs for background construction was 10 times more than for signal. The distance between photons in pair for both signal and background was required to be more than 36 cm (i.e. close photons will give only one local maximum in calorimeter and can not be reconstructed in a single event). The normalized background histogram was subtracted from signal histogram. The result for $\pi^0$ mass region is shown on figure 3 on the left plot. Used statistics was not enough to extract the mass peak of $\eta$-meson in the same way. To estimate required statistics invariant mass of reconstructed photon pairs originating from the same $\eta$-meson was histogrammed (see right plot on figure 3). The errors were calculated using subtraction technique used for reconstruction of
\( \pi^0 \) peak. The significance of \( \eta \)-meson peak is about 2.7 for a given statistics. About \( 10^7 \) central Au+Au collisions at 10 AGeV collisions should be enough for robust reconstruction of \( \eta \)-meson. This corresponds to about half of a minute running of CBM at \( 10^7 \) collisions per second.

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