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Simulation-based performance study of the neutron calorimeter for the compressed baryonic matter experiment

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The Neutron Calorimeter (NCAL), a new detector for the Compressed Baryonic Matter (CBM) experiment at FAIR, is designed to improve collision centrality and collective flow measurements in heavy-ion collisions while expanding CBM's physics scope by covering elementary particle interactions, such as proton-proton collisions. This study presents a performance evaluation of the NCAL system using Geant4 simulations, covering an energy range of 1 MeV to 10 GeV for neutrons and protons, with an emphasis on energy transfer and deposition characteristics. Simulations demonstrated unique detector response characteristics for neutrons and protons. Based on our findings, we are developing techniques to improve particle identification and expand our overall understanding of the detector response. Experimental validation is currently in progress via several experiments already performed at the mini-CBM facility at GSI. This project facilitates the integration and commissioning of NCAL for the CBM experiment at FAIR, thereby enhancing its performance for a broad range of future physics observations.

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1. Introduction

Unveiling the secrets of nuclear matter under extreme conditions requires sophisticated detection techniques. The Neutron Calorimeter (NCAL) is a neutron detection system foreseen in the Compressed Baryonic Matter (CBM) experiment [1]. The CBM experiment will use a particle beam from the SIS100 (100 T m) accelerator to investigate QCD phase transition at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany [2]. The NCAL is the newest member of the CBM detector family with the goal of improving the collision centrality and collective flow measurements, alongside the Forward Spectator Detector (FSD) [3]. While CBM mainly focuses on heavy ion reactions, the capabilities of the neutron detector might widen the CBM physics scope by opening up new opportunities. The CBM infrastructure for FAIR is still under construction. Currently, prototype detectors are being tested at a mini CBM (mCBM) experimental test setup using the existing GSI infrastructure [4].

The key detector components of the NCAL are repurposed elements from the Time-of-Flight (TOF) detector previously operated at the COoler SYnchrotron (COSY), of the Forschungszentrum Jülich (FZJ) [5]. For the test measurements at mCBM a small NCAL test unit was prepared, combined with additional scintillator plates to be used as veto-signal for the charged particles.

One of the key objectives in the performance studies of the neutron calorimeter is to characterize, evaluate, and understand its detection efficiency of the neutral particles. This process involves simulation as well as an experimental approach. In the scope of this paper, we will discuss the results from the latest Monte-Carlo simulations performed using Geant4 software and some of the latest ongoing experiments at GSI and UJV Rez (Czech Republic) [6].

2. Detector Systems Overview

2.1 Neutron Calorimeter

The NCAL system consists of modules constructed from BC–416 plastic scintillators [7]. Each module is hexagonal, with a side of roughly 8 cm and a total length of 45 cm. The full setup will have 86 modules, resulting in an active area of ~ 1.5 m^2. The collection of scintillation light is facilitated by the utilization of Photonis XP4592/PA photomultipliers (PMT)[8, p. 62]. A silicon-based gel between the light guide and the PMT ensures a good optical coupling and a consistent response. Modules are wrapped with layers of light-insulating sheets. For studying detector performance, two identical test configurations have been established, each comprising 7 modules; see Fig. 1. Both configurations are mounted on mobile and height-adjustable crates. One setup has been deployed in the mCBM experiment, whereas the other is utilized for a range of tests, including experiments conducted at the Rez facility in the Czech Republic and laboratory tests at the IKP institute, FZJ.

2.2 VETO System

The VETO system comprises five vertically hanging modules positioned in front of NCAL. To ensure NCAL active region coverage, each component is tilted at a small angle with a 1 cm overlap. These modules comprise thin 50 cm × 10 cm × 0.4 cm plastic scintillators glued to light guides at each end, which are linked to 9954B photomultiplier tubes at each panel's ends, thereby enhancing light collection, ensuring a consistent signal response, and delivering positional information of the particle hit [9].

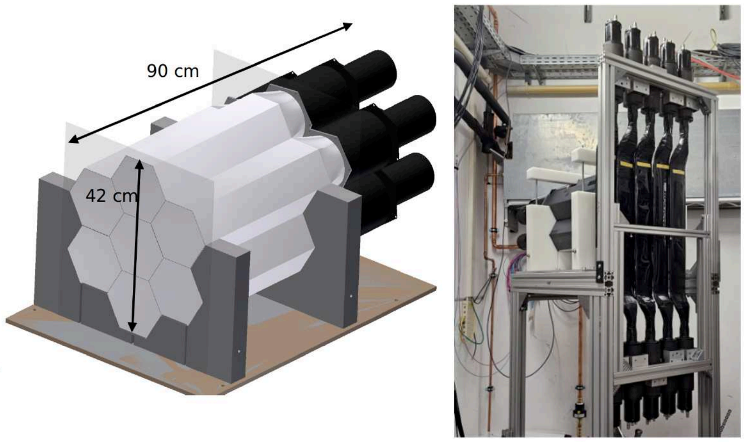

Figure 1: On the left side, a sketch of the NCAL test unit with seven scintillator modules is shown, and the right side shows a photo of the unit installed at mCBM with the veto scintillator system in front.

3. Monte-Carlo simulations using Geant4

The Geant4 modeling framework was set up to study the NCAL responses to neutrons and protons. Primary particles were sent from a G4ParticleGun to the NCAL central module from a fixed point on the beam axis. Simulations using both neutron and proton sources across an extensive energy spectrum - from 1 MeV to 10 GeV in decade increments—simulated 10,000 events at each energy level.

The simulation uses the QGSP_BERT physics list, which precisely simulates hadronic interactions within the relevant energy spectrum by integrating the Quark–Gluon String Precompound model for high-energy interactions, the Bertini cascade model for intermediate energies, and the Precompound model for nuclear de-excitation. Comprehensive event-by-event monitoring documents particle characteristics, paths, and energy deposition within the detector's structure. Post-processing analysis assesses key performance measures, such as detection efficiency, energy resolution, particle multiplicity, and energy distribution patterns, therefore offering significant insight into the operating aspects of the NCAL system.

3.1 Energy Transfer Calculations in the Central Module

This study investigates the energy transfer by the primary particle to the NCAL system during its interaction with the central module. Energy transfer histograms have been produced for proton and neutron beams at an incident energy of 1 GeV. It is important to note that the majority of the energy deposited by incident neutrons happens via inelastic hadronic interaction. The given energy is converted into secondary particles, which are subsequently identified. In contrast, the energy deposited for incident protons is predominantly determined by ionization losses, as described by the Bethe-Bloch equation. Similar investigations have been conducted for protons, neutrons, and some other particle types across a broad energy spectrum (ranging from 1 MeV to 10 GeV).

Figure 2 illustrates the total (in the neutron case, including all secondary particle cascades) deposited energies. For neutrons, the characteristic peak near the first bin is mainly attributed to neutron elastic scattering events within the core module. In elastic scattering, the neutron predominantly alters its trajectory while depositing just a minimal quantity of kinetic energy to the scintillator material. As a result, elastic neutron scattering, contributes negligibly to the observed energy within the calorimeter. Moreover, certain inelastic neutron interactions may lead to energy deposits that fall below the system's detection threshold, thereby diminishing the overall neutron detector efficiency. This observation highlights the inherent difficulty in neutron detection with calorimeters and stresses the necessity for advanced analytical methods to differentiate between neutral and charged particle interactions.

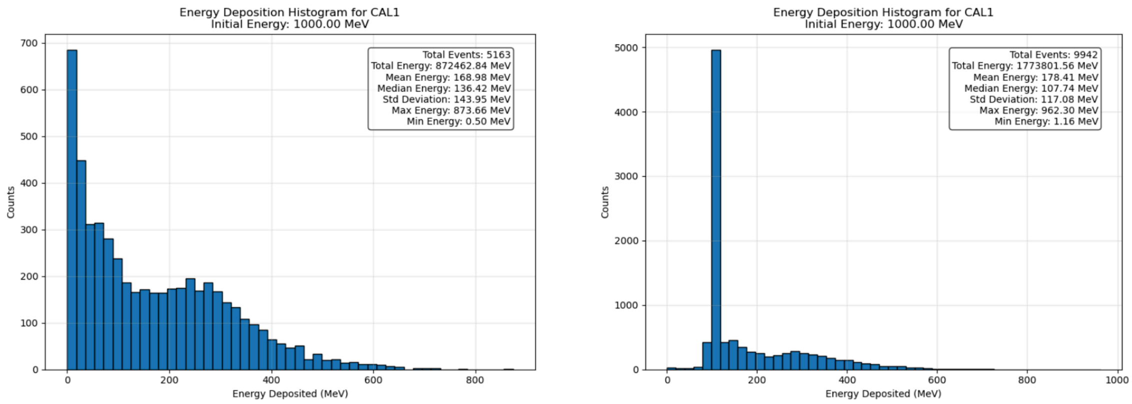

Figure 2: Energy deposition distribution histogram for 1 GeV a) neutrons and b) protons.

The right plot depicts the expected peak at ~ 100 MeV the region, proton ionization energy loss along the length of the NCAL, while neutrons have a much broader distribution, centered around 275 MeV. This observation will help us develop a technique for enhanced neutral/charged particle identification (PID) using neighboring module multiplicities, which we will discuss in the next section.

3.2 Neutral Particle Identification Enhancing Possibilities

Energy deposition studies for neutrons and protons in the central module, gave us an understanding of the expected different signatures in the signals from a single module in our system, but it also opened up possibilities of further enhancing the selection process by observing not just one but all modules as a whole system. Here, the number of modules in an event that have a deposited energy above threshold is called the "hit multiplicity". As shown in Fig. 3 the detector response of the whole system for a) neutrons and b) protons depicts different characteristics. Bin 0 accounts for non-detected hits by the NCAL system. Comparing hit multiplicities per event, protons show the majority of the events having only one hit in the central module; neutrons offer a broader distribution with multiple hits in the neighboring modules.

The veto detector remains the main tool for identifying charged particles in the NCAL system. Using time differences, PMT readouts on both ends give a hit position estimate. The detection efficiency of the veto detector is currently under investigation. Promising results from the presented simulations give us opportunities to further improve the particle selection process. Implementing complex algorithmic mechanisms for the PID faces challenges related to the readout systems and software, as will be discussed in the following Chapter 4.

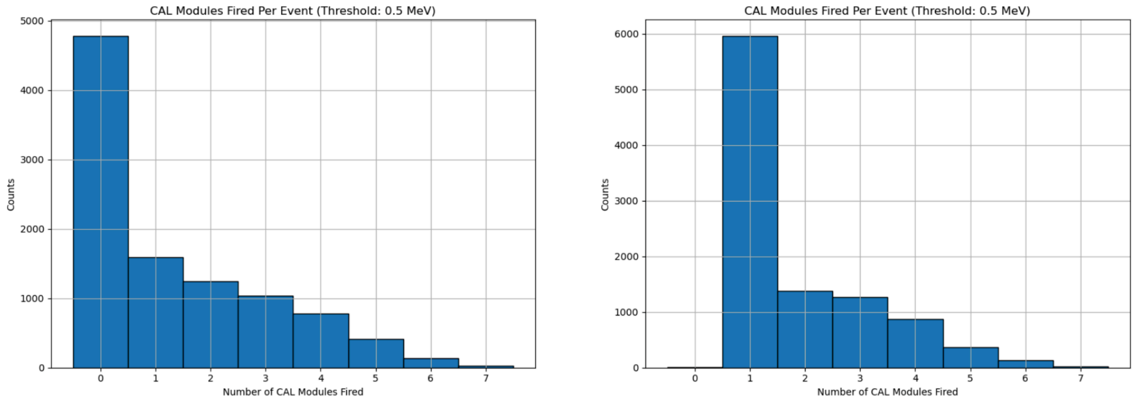

Figure 3: Hit multiplicity of the NCAL unit for 1 GeV a) neutrons and b) protons.

4. Experiments

The NCAL and Veto systems already participated in three different beamtime runs, with gold, nickel, and silver slow-extracted ion beams from SIS18 at mCBM. Energies ranging from $T = 1.2$ - 1.5 AGeV and an intensity of 1.5×10^7 per spill, provided reasonable conditions for single event selection for testing our systems as well as the whole DAQ chain. Preliminary analysis showed promising results.

The NCAL, Veto, and FSD detectors used the Ring Imaging Cherenkov Detector (RICH) readout chain [10]. The RICH readout systems offer time-over-threshold (TOT) information about the signal, which requires calibration for energy conversion. We conducted additional experiments with the help of the University of Wuppertal group, to characterize the TOT dependence on the NCAL PMT signal integral (corresponding to the energy deposition) at different signal attenuations and PMT voltage settings and developed algorithms for conversion. Additional measurements have been performed using a strontium-90 source and cosmic MIPs for Veto hit position identification and NCAL energy calibrations. Finally, for understanding NCAL neutron detection efficiency using predefined neutron beams, experiments in ÚJV Řež have been conducted [11].

5. Conclusions and Outlook

Simulations performed for the standalone NCAL test setup gave us insights into the detector's response to 1MeV - 10 GeV energy range for neutron and proton beams, further allowing the extension of the performance capabilities of the detector using a combination of single module characteristics of the response and the systemwide multimodule approach. Simulations suggest the NCAL neutron detection efficiency ~ 50 %, which aligns with previous studies performed at 2.7 GeV/c at COSY, where efficiency was estimated to be ~ 40 % [12].

We plan to conduct a detailed investigation of detector responses, including hit multiplicities, energy depositions, and hit timings for various particles and heavier fragments. Machine learning algorithms will be implemented to enhance PID.

Full integration into CBM software and DAQ systems, as well as commissioning, will continue for the following years. We will apply the knowledge we've gained from simulations to the data analysis of ongoing and future experiments.

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