Studies of nuclear equation of state with the HIRFL-CSR external-target experiment

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Abstract

The HIRFL-CSR external-target experiment (CEE), currently under construction, is expected to provide novel opportunities for studying the thermodynamic properties—specifically the equation of state of nuclear matter (nEOS)—through heavy ion collisions at beam energies of a few hundred MeV/u. Fast simulations of detector responses to collision events generated using transport models have been conducted based on Geant4 packages. The overall performance of CEE, including spatial resolution of hits, momentum resolution of tracks, and particle identification capability, has been investigated. Various observables proposed for probing the nEOS, such as light cluster production, the t/^{3He} yield ratio, radial flow, the π^-/π^+ yield ratio, and neutral kaon yields, have been reconstructed. The feasibility of studying the nEOS beyond saturation density through these observables, to be measured with CEE, has been demonstrated.

Full Text

Preamble

Studies of nuclear equation of state with the HIRFL-CSR external-target experiment

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The HIRFL-CSR external-target experiment (CEE) under construction is expected to provide novel opportunities for studying the thermodynamic properties—namely, the equation of state of nuclear matter (nEOS)—through heavy ion collisions at beam energies of a few hundred MeV/u. Based on Geant4 packages, fast simulations of detector responses to collision events generated using transport models have been conducted. The overall performance of CEE, including spatial resolution of hits, momentum resolution of tracks, and particle identification capability, has been investigated. Various observables proposed to probe the nEOS, such as the production of light clusters, the t/^{3}He yield ratio, radial flow, the π^-/π^+ yield ratio, and neutral kaon yields, have been reconstructed. The feasibility of studying nEOS beyond saturation density via these observables with CEE has been demonstrated.

Introduction

The phase diagram of nuclear matter is of fundamental significance for understanding the properties of the strong interaction described by Quantum Chromodynamics (QCD) and the evolution of the universe. Relativistic heavy ion experiments have revealed various signals indicating that strongly interacting matter may undergo a transition from the hadron phase to the quark-gluon plasma (QGP) phase, which is a crossover at low baryon density and high temperature [1–3].

Fig.1 shows the QCD phase diagram based on current understanding [4]. Despite substantial progress in this direction, several important questions concerning the QCD phase diagram remain unresolved. For instance, what are the thermodynamic properties of QCD, and where is the phase boundary between QGP and hadronic matter at high net-baryon density? Does a critical endpoint (CEP) exist, and if so, where is it located? To address these questions, systematic exploration of the QCD phase diagram is of great significance.

Relativistic heavy ion collisions (HIC) across a wide energy range provide the unique terrestrial method to study the QCD phase diagram. Over the past two decades, nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have collected extensive data searching for signals of a first-order phase transition and the precise location of the CEP. Between 2010 and 2017, RHIC completed the first phase of the Beam Energy Scan program (BES-I) [5, 6]. The second phase (BES-II) was launched in 2018, focusing on collisions with √s_{NN} = 27 GeV to study sensitive observables of QCD phase transitions [7–9], including net-proton [4, 10–13], net-charge [14], and net-kaon multiplicity distributions and higher-order moment analysis [15].

Fig.2 shows the energy dependence of net-proton high-momentum σ^2 in Au+Au collisions at 0–5% centrality from RHIC BES-I [4]. The σ^2 of net-protons is closely related to that of protons and exhibits a non-monotonic dependence on collision energy with a significance of 3.1σ [11, 13]. In addition, predictions from the UrQMD calculation, which incorporates conservation laws and most relevant physics but excludes phase transitions and mean-field potentials, do not coincide with the trend of the data points at low energies. This indicates that accurate measurements in the supra-saturation density region and at lower beam energies are crucial to further reduce experimental uncertainties. In addition to existing facilities, many more experiments are scheduled, such as CBM at FAIR and MPD at NICA.

In the hadron phase, the key component of the QCD phase structure is the equation of state of nucleonic matter (nEOS) [16]. For convenient definition of nEOS, the nucleon specific energy E(, δ) of nucleonic matter at zero temperature is written in quadratic form:

E(, δ) = E_0( ) + E_{sym}( )δ^2

where δ = (_n - _p)/(_n + _p) is the isospin asymmetry, and _n and _p are the neutron and proton densities, respectively. E_0( ) is the nucleon specific energy in symmetric nuclear matter, and E_{sym}( ) is the density-dependent nuclear symmetry energy. Keeping the lowest-order terms, the nEOS for symmetric nuclear matter can be written as:

E_0( ) = E_0(${}_0$) + (${}_0$/2)((- ${}_0$)/(3 ${}_0$))^2 + (J_0/6)((- ${}_0$)/(3 ${}_0$))^3 + (Z_0/24)((- ${}_0$)/(3 ${}_0$))^4

where the coefficients ${}_0$, J_0, and Z_0 are the incompressibility, skewness, and kurtosis parameters, respectively. The nuclear symmetry energy is expressed as:

E_{sym}( ) = E_{sym}(${}_0$) + L((- ${}_0$)/(3 ${}_0$)) + (K_{sym}/2)((- ${}_0$)/(3 ${}_0$))^2

where L and K_{sym} are the slope and curvature parameters of the nuclear symmetry energy at normal nuclear matter density ${}_0$, respectively.

In heavy ion collisions from a few hundred MeV/u to a few GeV/u, nuclear matter above saturation density is created. Density gradients in the compressed nuclear matter develop into various forms of flow that carry information about the nEOS, and in turn, these flows have been used to probe the incompressibility of nuclear matter [17]. Recently, the HADES collaboration published proton triangular flow v_3 data at 2.4 GeV. Compared to UrQMD transport model calculations, the proton v_3 exhibits high sensitivity to the hadronic medium EoS [18]. In addition to flow analysis, the production of K mesons, particularly near threshold, is sensitive to the density of the compressed participant region and thus serves as a probe of nEOS. Thanks to great efforts from the nuclear physics and astrophysics communities, knowledge of E_0( ) from $_0$ to a few times $_0$ has been accumulated.

The least known term of nEOS is the density behavior of symmetry energy E_{sym}( ). Since E_{sym}( ) gives rise to isospin diffusion and drift mechanisms, heavy ion collisions involving neutron-rich nuclei in terrestrial laboratories provide unique opportunities to constrain E_{sym}( ) near and above saturation density. Across a wide energy range, various isospin probes have been identified and applied to constrain E_{sym}( ) near and above $_0$ [19–26]. Some new probes have also been introduced or updated recently, including the neutron skin thickness of heavy nuclei [27, 28], the angular distribution of average N/Z of light charged particles [29], the anticorrelation of the t/^{3}He yield ratio with $_0$, and the π^-/π^+ ratio for $>$ $_0$ [30, 31]. Moreover, since the observation of the neutron star merger event GW170817, great progress has been made in constraining E_{sym}( ) by combining GW170817 and heavy ion data [32, 33]. For a recent review, see [34].

Despite substantial progress achieved in the last two decades, constraints on E_{sym}( ) still suffer from large uncertainties [33, 36–39], particularly in the high-density region. Worldwide efforts in this direction remain ongoing. To finally determine E_{sym}( ) in the supra-saturation density region, new experiments are scheduled or have been conducted at major scientific facilities worldwide, including but not limited to HADES at GSI, SπRIT at RIKEN, and RAON-LAMPS in Korea. These latest experiments will certainly provide better experimental conditions, improve statistics, and reduce uncertainties. For a recent review, see the long report [40].

To this end, in addition to the RHIC-STAR energy scan experiment, several large experimental facilities are in operation or under construction worldwide that are crucial for mapping the QCD phase diagram at high net baryon density and constraining the nEOS in the hadron phase. In addition to the aforementioned facilities, CEE is currently under construction at the T4 Experimental Terminal of the Heavy Ion Research Facility (HIRFL) in Lanzhou [41, 42], aiming to collect first physics data by 2025. The High Intensity Heavy Ion Accelerator Facility (HIAF) is under construction in Huizhou, China [43]. HIAF is designed to provide beams of all ion species, with the highest center-of-mass energy in U+U collisions being √s_{NN} = 4 GeV. The upgraded CEE+ will be placed at terminal T2 of HIAF for high-energy experiments, providing excellent opportunities to study QCD phase structure in high baryon density regions and the EoS of nuclear matter at high density.

This paper introduces the design, performance, and feasibility of various physics goals related to EOS studies with CEE. Simulations are carried out within the Geant4 framework. The ultra-relativistic quantum molecular dynamics (UrQMD) model, which incorporates the Skyrme potential energy density functional and in-medium nucleon-nucleon cross sections, is adopted as the event generator [44–46]. Analysis and reconstruction of simulated data are performed on the CEE-ROOT platform, developed by the CEE collaboration and based on FairRoot [47].

The paper is organized as follows. Section II presents the technical design of CEE and the main functions of each detector subsystem. Section III introduces the expected performance of CEE, including spatial acceptance, momentum resolution, PID capability, and the construction of the CEE global trigger signal. Section IV presents verification of several probes sensitive to the EOS of nuclear matter beyond saturation density, including light cluster yields, radial flow, π^-/π^+ ratio, and neutral kaon yields. Section V provides a summary.

II. Structure and Simulation of CEE

A. Structure of CEE

Aiming to study the EOS of nuclear matter at approximately 2 $_0$, where $_0$ is the saturation density, CEE is designed to measure charged particles over nearly 4π solid angle in the center-of-mass frame [41]. The CEE design is shown in Fig.4. The main component is a large-gap dipole magnet housing tracking detectors in a nearly homogeneous 0.5 T field along the vertical direction. The target is located inside the field, enabling tracking detectors to cover a large solid angle. The tracking detectors include two time projection chambers (TPC) [48] surrounded by inner time-of-flight (iTOF) detectors covering midrapidity [49], and an array of three multiwire drift chambers (MWDC) followed by an endcap time-of-flight (eTOF) wall for measuring charged particles at forward rapidity [50]. At the downstream end of the CEE spectrometer, an array of plastic scintillators measures charged particles near zero degrees (ZDC) [51]. The start timing detector (T0) [52, 53] and active collimator (AC) are placed on the beam line upstream of the target. Additionally, a silicon pixel positioning detector (SiPix) [54, 55] monitors the beam position upstream of T0. Table I shows the main technical specifications of the CEE system.

The midrapidity tracking detectors consist of two identical TPCs surrounded by iTOF walls. The TPCs are installed in a left-right symmetric configuration to leave 20 cm space between them for the beam to pass through. The target position is in the gap between the two TPCs, 15 cm from the rear surface of the field cage. TPC electronics are placed on the top plane above the TPCs. High voltage is fed into the field cage from the bottom plane. A high-voltage step-down structure surrounded by Teflon blocks is designed to avoid sharp voltage drops near the HV point. The field cages are made of Kapton layers with copper electrodes printed on both surfaces, ensuring electric field distortion of less than 0.1%. Three layers of large-area gaseous electron multiplier (GEM) foils are stacked on top of the TPC sensitive volume to amplify arriving electrons and induce signals on readout pads. Signals from each pad are read out by specially designed front-end electronics (FEE) and transferred to digitization boards using SAMPA chips [56, 57].

The forward tracking detectors consist of three MWDCs and an eTOF wall placed at forward angles. Two MWDC sets are placed inside the dipole field, and the third one, followed by the eTOF wall, is placed outside the magnet. Each MWDC and the eTOF wall have an inactive area designed for beam particles to pass through without inducing enormous charges in the detector sensitive volumes. Each MWDC contains six layers of sensitive wires in three directions (X, U, and V), oriented at 0°, +30°, and -30° with respect to the vertical direction. For each wire direction, there are two layers of drift cells displaced by half a cell size to discriminate ghost hits. Both entrance and exit windows of the MWDCs are made of aluminum-coated Mylar foil. The detector operates in atmospheric flow-gas mode. High voltage is fed directly to the anode wires. Signals, read out via capacitive coupling, are amplified and shaped in the FEE before being transferred to an SCA chip for digitization. The digitized data are then sent to the BDM module, where timing and amplitude information are computed online and transferred to the DAQ system for storage. Table II lists the main geometric dimensions and technical specifications of the TPC and MWDC.

Time-of-flight (TOF) signals are measured by T0, the inner TOF wall (iTOF), and the outer TOF wall (eTOF). T0, placed in front of the target and made of scintillator foil read out by SiPM from the side, delivers the initial time of heavy ion collisions. Both iTOF and eTOF, consisting of multi-gap resistive plate chambers (MRPC), record the arrival time of charged particles passing through the TPC and MWDC, respectively. Combining tracking and TOF detectors allows PID information to be deduced via dE/dx and p/Q, where p is momentum and β is velocity calculated from track length and TOF. Table III shows the main performance characteristics of the TOF system. The total area of iTOF and eTOF systems is about 12 m^2.

In p/Q determination from tracking detectors and β from iTOF and eTOF, the hit position can also be derived through the time difference of signals at both ends. The iTOF, grouped by modules, surrounds the left, right, and bottom surfaces of the TPC. The upper surface is not covered by TOF detectors because TPC readout electronics are arranged on top. The left and right iTOF walls consist of six iTOF modules, each containing three MRPC detectors with envelope dimensions of 1000(y) × 1355(z) mm^3. The bottom iTOF wall contains two symmetrical parts, consisting of 6 iTOF modules and 12 MRPC detectors, with a bottom envelope size of 670(x) × 100(y) mm^3. The eTOF wall is located at the downstream end of the dipole magnet, 2.6 m from the target. Each MRPC has 10 0.25 mm air gaps, with self-sealing technology applied for the first time. The entire wall is divided into 7 modules, each containing 3-4 self-sealed MRPCs [50]. TOF detector signals are collected and amplified by the MRPC special electronics chip NINO [58] in the FEE, and high-precision timing information is obtained through the high-performance time digitization module (TDM) [59].

The active collimator, which vetoes off-target reaction background, is placed between T0 and the target. It consists of four plastic scintillators (250 × 250 mm^2) distributed around a 50 × 50 mm^2 hole at the chamber center. SiPMs are used to read out the signals.

The ZDC primarily measures spectators from HIC and determines collision centrality and reaction plane. Located at the most downstream position of the spectrometer, about 300 cm from the target, the ZDC has a rotationally symmetric layout about the beam line. It is divided into 24 equal sectors, each containing 8 trapezoidal scintillators placed in a row along the radial direction. The outer radius of the ZDC sensitive area is 100 cm, while the inner radius is about 10 cm, through which non-reacted beam particles can pass.

The large-gap superconducting dipole magnet bends charged particles produced in projectile-target collisions. The magnet's raw dimensions are 2700(L) × 1200(W) × 4300(H) mm^3. The uniform field region housing the TPC sensitive volume is 900(L) × 800(W) × 1200(H) mm^3. The central field strength is 0.5 T with uniformity better than 5%. Fig.5 shows the magnetic field distribution in the center of the dipole magnet.

In addition, CEE includes supporting systems. The data acquisition system (DAQ) uses D-Matrix architecture for data storage. The clock system provides high-precision global synchronous clocks for electronics modules and the DAQ system. The trigger system provides global trigger signals for beam experiments and detector test runs. See Section III.C for details on constructing CEE's global trigger signals.

B. Event Generator and Simulation Tool

To constrain nEOS, particularly for supra-saturation density, one typically uses given E_0( ) and E_{sym}( ) as input in transport models for HIC or in solving the Tolman–Oppenheimer–Volkoff (TOV) equations for neutron star structures. Predicted results are then compared to experimental data or astrophysical observations. By adjusting parameters of E_0( ) and E_{sym}( ) until results converge to experimental data, one obtains constraints on nEOS. In turn, transport models are typically employed as event generators in feasibility studies of nEOS via terrestrial heavy ion experiments.

The UrQMD model is a widely used transport model describing relativistic heavy ion collisions and proton-induced reactions [60, 61], covering energies from sub-GeV/u to TeV/u at SIS, AGS, SPS, RHIC, and LHC. To apply UrQMD as an event generator for CEE, the model has been improved with isospin-dependent nuclear potentials and collision terms. The UrQMD event generator is operated by Huzhou University in China [44–46], with main improvements including: (1) implementation of the mean-field potential derived from the Skyrme potential energy density functional [46, 62, 63]; (2) consideration of nuclear medium effects on N-N cross sections, adopting density-, momentum-, and isospin-dependent N-N cross sections [44, 64–66]; (3) adoption of the isospin-dependent minimum spanning tree (iso-MST) method [67] for cluster construction. Additionally, yield and flow observables for π and K, which are effective and sensitive probes of symmetry energy, can be better reproduced by introducing proper pion-nucleon and kaon-nucleon potentials [33, 68, 69].

The effective two-body interaction potential energy U is decomposed into Coulomb energy U_{Coul}, Skyrme potential energy U_ , and momentum-dependent potential energy U_{md}. U_ and U_{md} are written as:

U_ ,md = u_ ,md d^{3}r

where

u_ = (α/2)(/ $_0$)^ + (β/2)(/ $_0$)^γ + g_{sur}( )^2/ + g_{sur},iso[(_n - _p)]^2/ + u_{sym}

u_{md} = t_{md} ln^2[1 + a_{md}(p_i - p_j)^2]

The symmetry potential energy density functional reads:

u_{sym} = A_{sym}(_n - _p)^2/ $_0$ + B_{sym}(_n - _p)$^{\{\gamma+2\}/ _0}${γ+1} + C_{sym}(_n - _p)^2(/ $_0$)^{2/3}/ $_0$

For Skyrme interactions, symmetry potential energy terms arise from two-body and three-body interaction terms, with parameters A_{sym}, B_{sym}, and C_{sym}. All parameters used in UrQMD, such as α, β, , g_{sur}, g_{sur},iso, A_{sym}, B_{sym}, and C_{sym}, can be derived from standard Skyrme parameters x_0, x_1, x_2, x_3, t_0, t_1, t_2, t_3, σ [62, 63, 70]. Additionally, one can set A_{sym} = C_{sym} = 0 and B_{sym} = C_s/2, adopting a density power-law form to investigate density-dependent symmetry energy [70, 71].

Simulations and reconstructions of the CEE experiment are implemented in the CEE-ROOT framework, a platform based on FairRoot software [47] built on ROOT and Geant4 packages. User routines complete data calibration, event reconstruction, efficiency correction, and histogram filling. In CEE-ROOT, subdetectors, dipoles, and main materials are constructed using Geant4 class libraries. When particles produced in HIC from the event generator are input to the simulator, particle propagation and detector responses are simulated. Signals in detector sensitive volumes are digitized and saved to disk for reconstruction. In these studies, detector systems including the magnetic field, T0, iTOF, eTOF, TPC, MWDC, and ZDC are constructed as designed. The improved UrQMD model described in Section II.A serves as the event generator. Fig.6 shows the event display and detector configuration in simulations. Detector performance based on fast simulations is introduced in the next section.

III. CEE Performance Study

This section presents fast simulation studies of CEE performance. Using symmetric ^{208}Pb+^{208}Pb collisions, acceptance, PID capability, and centrality selectivity are discussed. The design of the global trigger for heavy ion collisions in CEE is introduced.

A. Acceptance

Studies of nuclear EOS and QCD phase structure typically require measurement of nearly all reaction products, naturally favoring large acceptance for CEE. Fig.7 shows the phase space distribution of different particle species at b = 0 fm in ^{208}Pb+^{208}Pb collisions at 0.3 GeV/u. The abscissa is reduced rapidity defined by $y^{(0)}$ = y_{lab}/y_{cm} - 1, where y_{lab} is particle rapidity in the laboratory frame and y_{cm} is the center-of-mass rapidity of the collision system. The ordinate corresponds to reduced transverse velocity t = p_t/(mβ_bγ_b), where p_t and m are transverse momentum and particle mass, respectively, and βb *and* γb are the beam velocity and corresponding Lorentz factor in the laboratory frame. Curves for different laboratory angles are overlaid on the data. The MWDC array covers angles below 30°, while the TPC mainly covers *{lab} > 30°. Since the target is placed between the two TPCs, 15 cm from their rear ends, space at large angles with* {lab} > 90° is also partially covered. The phase space distribution of protons shows that both TPC and MWDC have detection capability near 30°, creating an overlap region. More than 90% of center-of-mass phase space can be covered, particularly for symmetric systems where distributions can be reflected about $y^{(0)} = 0$ based on physical requirements.

Fig.8 shows scatter plots of momentum p versus _{lab} for protons, tritons, π^+, and π^- in ^{208}Pb+^{208}Pb reactions at 0.3 GeV/u in the laboratory frame. Distributions pass only TPC and MWDC filters with a track length cut L_{trk} > 30 cm, without TOF hit conditions. The wide angular acceptance of the tracking detectors is clearly illustrated.

Fig.9 further presents angular coverage of tracking detectors TPC and MWDC on the -ϕ plane for protons. Particles with track lengths shorter than 30 cm in the TPC are cut. While polar angle is well covered for _{lab} < 100°, there is obvious efficiency loss in azimuth near ϕ = 90° and 270°.

B. Particle Identification

Since CEE has two tracking detectors (TPC and MWDC) and TOF detectors, both dE/dx and p/Q methods can be applied. In simulation studies, for dE/dx-p/Q correlation from TPC and MWDC, total energy loss dE is accumulated in each step as particles propagate through the sensitive volume filled with working gas (90% Ar + 10% CO_2). When a complete cell is processed, the energy loss rate dE/dx is calculated by summing energy losses in all steps and smearing by a given variance. Since the dE/dx distribution follows the Landau formula with divergence at large values, a high-energy cut is typically applied when filling histograms. Momentum p is obtained by fitting hits from ionization of energetic particles during propagation. Track finding is not yet implemented, so fitting is done directly on each individual track with smearing introduced according to the tracking detector's position resolution.

Fig.10 presents dE/dx versus p/Q for TPC and MWDC. Different isotopes with Z = 1 and Z = 2 can be well identified in the TPC. In MWDC, due to only 18 sampling layers (corresponding to 18 anode wire planes), momentum determination is moderately degraded, though tracking residual is controlled within 300 m.

With increasing p/Q, separation between neighboring bands in dE/dx-p/Q is reduced, particularly between pions and protons beyond 1 GeV/c. TOF correlation is therefore applied to improve PID capability. Once track length L_{trk} is determined by tracking detectors, particle velocity can be calculated and mass m resolved at given momentum p by:

β = L_{trk}/(c $\cdot$ t_{TOF})

where c is the speed of light. This method applies to both TPC+iTOF and MWDC+eTOF configurations. To achieve intended performance, timing resolutions of iTOF and eTOF are designed as 50 ps and 60 ps, respectively. Fig.11 shows particle velocity as a function of momentum p measured in the TPC. Pions and Z = 1 isotopes are well separated.

Fig.12(a) shows mass-momentum correlation by combining eTOF time-of-flight information with MWDC momentum information. The mass distribution is plotted in Fig.12(b). At the beam energies of interest, light charged particles with Z = 1 can be clearly separated, although small distortion occurs at low momentum due to detector gap effects not corrected in track length estimation.

Momentum resolution for tracks in the B field is determined by hit position resolution and track length L in the bending area:

$(\sigma p/p)^2 = (\sigma\{\mathrm{xz}\}/(0.3\mathrm{BL}^2))^2 + (4/\mathrm{N})(\sigma\_\ /\ )^2 + (\cot\ \cdot\sigma\ )^2 + (L\{\mathrm{trk}\}/\mathrm{X}_0)\sin^2$

where B is magnetic field strength,   is polar angle, N is sampling number, σ_{xz} and σ_ are hit position resolution in the x-z plane perpendicular to B and angular resolution, respectively, and X_0 = 1.2 m is the radiation length. Given hit position uncertainties, momentum resolution can be investigated through fast simulations.

Fig.13 shows momentum resolution reconstructed from TPC hit information for 0.3 GeV/u ^{208}Pb+^{208}Pb at b = 0 fm, using σ_{xz} = 0.6 mm and σ_ = 0.5°. Typical resolution for $\pi\pm$, protons, and deuterons is about 5%. With increasing momentum or in forward angles, momentum resolution gradually degrades, demonstrating the necessity of a forward-angle tracking detector array for dipole spectrometers—hence the MWDC array design for CEE. Degradation at low momenta mainly results from tracking efficiency loss, as low-momentum tracks leave very short lengths in the sensitive volume.

C. Global Trigger Signal Construction

In CEE beam experiments, global physical trigger signal construction serves two goals: (1) selecting collisions on the target and suppressing background events on the beam path, and (2) providing trigger signals for events of given geometry (collision centrality). Similar schemes are used in existing spectrometers such as FOPI [73] and SAMURAI [74].

At CEE, multiplicity of charged particles firing fast detectors (iTOF and eTOF) is employed to construct the global trigger because it provides an approximate measure of collision centrality. Fig.14 presents charged particle multiplicity as a function of impact parameter b in transport model simulations of ^{208}Pb+^{208}Pb at 0.5 GeV/u. Multiplicity distributions before (open) and after (solid) iTOF and eTOF filtering are shown. The multiplicity of charged particles firing iTOF and eTOF is clearly anti-correlated with b, providing centrality selection capability for the CEE spectrometer trigger signal.

IV. Study on the EOS of Nuclear Matter

This section presents feasibility studies of nuclear equation of state measurements using selected observables at CEE. In HIC in the hundreds of MeV/u energy domain, nuclear matter can be compressed to approximately 2 $_0$. Due to large stopping and extended space-time volume, observable sensitivity to nEOS is expected to be enhanced [75, 76]. It is therefore important to verify whether EOS information carried by various observables remains discernible at CEE.

A. Light Nuclear Production

One physics goal of CEE is systematic measurement of ^{3}H and ^{3}He production at beam energies between 300 and 600 MeV/u. This measurement aims to understand the correlation between clustering and isospin transport in HIC to achieve more stringent constraints on nuclear symmetry energy. The ^{3}H/^{3}He yield ratio in HIC across a wide energy range has been proposed as a sensitive probe of nuclear symmetry energy [77–84]. However, the origins of ^{3}H and ^{3}He are complex, and clustering is reportedly correlated with isospin degree of freedom transport. Experimentally, in the ~1 GeV/u regime, systematic data on pion, proton, and light cluster production including ^{3}H and ^{3}He have been published by the FOPI collaboration [17, 85], though the ^{3}H/^{3}He puzzle has been reported in other experiments [86, 87].

To measure the ^{3}H/^{3}He ratio, events generated by the UrQMD model are analyzed in the CEE-ROOT fast simulation framework. Fig.15 presents the ^{3}H/^{3}He ratio as a function of beam energy for ^{208}Pb+^{208}Pb system with different symmetry energy slope parameters $\gamma = 0.5$ (soft) and 1.0 (stiff). Charged products are filtered by tracking detectors. The yield ratio shows sensitivity to E_{sym}( ), with differences between $\gamma = 0.5$ and 1.0 preserved after detector filtering.

To clarify whether symmetry energy affects clustering, one can investigate clustering degree through the ratio of free protons to protons bound in clusters produced in HIC. In general, isospin-dependent N-N cross sections, nuclear symmetry potential, and Coulomb interactions are convoluted in cluster formation and free proton emission. Therefore, free proton yield relative to bound protons presumably carries information about nuclear symmetry energy E_{sym}( ), though system evolution from early compression to freeze-out is complex and model-dependent.

Fig.16 presents the excitation function of the free-to-bound proton ratio for central ^{208}Pb+^{208}Pb collisions at 300 MeV/u using $\gamma = 0.5$ and 1.0. Bound proton yield counts charges of light particles with $Z < 3$ in the reaction final state, including d, t, ^{3}He, and ^{4}He. The ratio increases gradually with beam energy, indicating clustering is more favored at low beam energy. Moreover, clustering degree, measured by Y_{free}/Y_{bound}, can differentiate E_{sym}( ) stiffness. With softer symmetry energy ($\gamma = 0.5$), more protons are found in clusters.

B. Radial Flow and EoS of Nuclear Matter

Collective flow has long been recognized as an observable of great significance for studying the equation of state of nuclear matter under extreme conditions [88–94]. Depending on collision geometry, collective flow takes different forms. In non-central collisions, collective motion manifests as directed flow and elliptic flow, representing the first and second Fourier coefficients of final product azimuthal distributions [95]. In central collisions, the fireball experiences compression followed by expansion, forming radial flow [96]. Radial flow magnitude depends on nuclear matter compressibility [84, 97], as demonstrated by FOPI collaboration showing radial flow sensitivity to nuclear matter incompressibility coefficient [85].

Radial flow can be extracted from transverse momentum spectra of final particles at midrapidity in central collisions. Two methods have been developed to obtain expansion velocity β_r: fitting p_t spectra using the Siemens-Rasmussen formula [98], or extracting mean kinetic energy dependence on final product mass based on the blast-wave model [99–101]. Both methods include thermal motion characterized by temperature T and expansion velocity β_r.

Here we study radial flow using the Siemens-Rasmussen formula:

d^{2}N/(dp_t dy$_0$) = CE e^{-γE/T} [γ + (T/(β_r p_T)) sinh(α)] cosh(α)

where γ = 1/√(1-β_r^2), α = β_r p_T γ/T, and E and p are particle energy and momentum in the center-of-mass frame. Radial expansion velocity β_r, thermal freeze-out temperature T, and constant C are fitting parameters.

Fig.17 demonstrates radial flow measurement feasibility in central ^{208}Pb+^{208}Pb collisions at CEE. Panel (a) presents p_t spectra for protons, deuterons, and tritons. Low-momentum parts are filtered by acceptance and track length cuts. Curves show simultaneous fitting results using the formula. The p_t spectra are reproduced fairly well. Panel (b) plots the minimum ^{2} distribution on the T-β_r plane, showing that simultaneous fitting determines both parameters well, while individual fits to $Z = 1$ isotopes correlate the parameters.

Fig.18 presents excitation functions of β_r (a) and T (b) reconstructed from simulations with   = 200 and 280 MeV. Transport model simulations reveal that different incompressibility leads to different freeze-out temperature T and expansion velocity β_r. With soft incompressibility, T is relatively higher and β_r lower, and vice versa. Differences exceed 10% in most cases, suggesting that stiff nuclear matter causes more violent compression and expansion, while soft nuclear matter converts more kinetic energy to thermal energy during collisions. CEE thus has capability for radial flow studies in heavy system collisions.

C. π^-/π^+ Yield Ratio and Symmetry Energy

The π^-/π^+ yield ratio produced in HIC has been proposed as a sensitive probe of nuclear symmetry energy at supra-saturation densities [25, 79, 102–104]. In transport models, pions are mainly produced via Δ resonances [33, 105]. From the isobar model, the initial ratio $(\pi^-/\pi^+)\{res\} = (5N^2 + NZ)/(5Z^2 + NZ)$ $(N/Z)^2${dense}, where N and Z are neutron and proton numbers in the reaction participant region. Therefore, (π^-/π^+)*{res} directly measures isospin asymmetry (N/Z)*{dense}, which is enhanced relative to the whole system due to isospin fractionation from E_{sym}( ). Consequently, the π^-/π^+ yield ratio becomes a sensitive probe of E_{sym}( ) [102]. In [106], the π^-/π^+ ratio is related in a statistical model to neutron and proton chemical potentials: π^-/π^+ exp[2(_n - _p)/T], where T is system temperature and _n - _p depends on E_{sym}( ) [107]. Circumstantial evidence for soft E_{sym}( ) has been found in FOPI pion data consistent with the isospin fractionation picture [20]. However, conclusions remain inconclusive due to model and observable dependencies, since pion production, transport, and clustering are complex in transport models [36, 37, 108].

Pion physics is therefore a focus at CEE. In the current CEE design, as shown in Figs.7(f) and (g) in Section III.A, the whole pion phase space in the u(0) plane is well covered, though azimuthal efficiency is lost near $\phi = 90°$ and 270° in the laboratory. With current efficiency, final π^-/π^+ yields in ^{208}Pb+^{208}Pb reactions at various beam energies are extracted and plotted in Fig.19 for $\gamma = 0.5$ and 1.0. The π^-/π^+ ratio decreases with increasing beam energy. Differences between $\gamma = 0.5$ and 1.0 are more pronounced at lower beam energy, consistent with previous predictions for Au+Au systems [37]. This trend results from larger fireball space-time volumes at lower energies [75]. At CEE's favorable energy region near 300 MeV/u, stiffness of E_{sym}( ) between $\gamma = 0.5$ and 1.0 can be discriminated if systematic errors are controlled within 10%.

D. K^0_S and Incompressibility

Finally, we briefly discuss kaon production and detection at CEE. Kaons are mainly produced in the supra-saturation density zone created in early collision stages, with typical channels B + B → Y + K. Kaon production is of interest in this energy region as a clean probe of nuclear EOS because kaons experience much less rescattering than nucleons or pions. The kaon yield has long been recognized as an effective probe of supra-saturation denisty nuclear matter EOS

[109]. The KaoS collaboration at GSI measured K^+ yields in C+C and Au+Au systems from 800 MeV/u to 1.6 GeV/u. Within transport models, the K^+ yield ratio between the two systems favors soft nuclear matter [110, 111].

Compared to charged kaons, the neutral kaon K^0 is unaffected by Coulomb interactions, so its production carries information about the high-density medium where it was produced. Yields of these neutral strange particles were studied in detail at SIS, BEVALAC, and AGS [68, 112, 113]. The K^0 yield increases with system size and shows significant dependence on nuclear matter incompressibility . As long as systematic uncertainties can be controlled within 10%, neutral kaon K^0 production can serve as a probe of nuclear equation of state, supporting one of CEE's physics programs.

Since HIRFL-CSR can provide proton beams up to 2.8 GeV and carbon beams up to 1.2 GeV, kaon experiments are possible at CEE. While K^+ identification may suffer from heavy backgrounds from protons and pions, our first step is to measure neutral K^0 decaying to π^+ and π^-, which are easier to detect. Fig.20 shows the invariant mass spectrum of π^+ and π^- in p+Ni system at = 200 MeV. After background subtraction using the mixing-event method, a peak at the K^0 mass is clearly visible. In 1 M simulated central collision events, about 200 K^0_S are reconstructed. The background is not fully removed, with enhancement at the low-mass end possibly due to residual baryon-baryon correlations since most pions are produced via Δ resonances. Compared to Monte Carlo truth tracks, the K^0_S reconstruction efficiency is about 0.46.

Fig.21 shows reconstructed K^0_S yield (mainly K^0_S) as a function of system size for two incompressibility coefficients = 200 and 280 MeV. The K^0 yield increases with target mass and shows significant dependence on incompressibility.

V. Conclusion

The conceptual design of CEE is briefly described. Expected performance is studied based on Geant4 simulations using UrQMD as the event generator. The main detector system is a large-acceptance magnetic dipole housing tracking detectors and surrounding TOF detectors. TPC and MWDC cover midrapidity and forward rapidity regions for tracking, respectively. TOF detectors (iTOF and eTOF) provide main trigger signals constructed using advanced FPGA technology.

In the CEE-ROOT framework, built specifically for CEE R&D, we have discussed feasibility studies of nuclear equation of state through various observables: light cluster production, ^{3}H/^{3}He yield ratio, radial flow, pion ratio, and near-threshold kaon production. Simulation results suggest these probes can be measured with CEE, providing opportunities to study properties of dense nuclear matter in the HIRFL-CSR energy regime.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Note: Figure translations are in progress. See original paper for figures.