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Abstract

Quantum Chromodynamics (QCD) phase diagram structure and phase transition critical points are active research areas in high-energy physics theory and experiment. Relativistic heavy-ion collisions serve as a powerful tool for exploring QCD phase diagram structure and searching for QCD phase transition critical points. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the United States is one of the world's major experimental facilities for high-energy heavy-ion collisions, with the STAR (Solenoidal Tracker at RHIC) experiment dedicated to experimental investigations of Quark-Gluon Plasma (QGP) properties at high temperature and density, as well as QCD phase structure. This article focuses on reviewing recent research progress from RHIC-STAR energy scan experiments on the search for the QCD phase transition critical point through higher-order moments of conserved charges and light nuclei production, and concludes with an outlook on future studies of QCD phase structure in the high baryon density region.

Full Text

Preamble

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Experimental Study of the QCD Phase Diagram in Relativistic Heavy-Ion Collisions

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Abstract

The structure of the Quantum Chromodynamics (QCD) phase diagram and the location of the critical point represent major research frontiers in both theoretical and experimental high-energy physics. Relativistic heavy-ion collisions provide a powerful tool for exploring the QCD phase diagram and searching for the QCD critical point. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is one of the world's major facilities for high-energy heavy-ion collisions, and the Solenoidal Tracker at RHIC (STAR) experiment is dedicated to studying the properties of Quark-Gluon Plasma (QGP) under extreme temperature and density conditions, as well as the QCD phase structure. This review focuses on recent progress from RHIC-STAR's Beam Energy Scan program in using higher-order moments of conserved charges and light nuclei production to search for the QCD critical point, concluding with future prospects for investigating the QCD phase structure in high baryon density regions.

Keywords: QCD phase diagram, relativistic heavy-ion collisions, QCD critical point, fluctuations of conserved quantities, light nuclei production

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The strong interaction is one of the four fundamental forces in nature, and Quantum Chromodynamics (QCD) is the underlying theory describing it. The strong force binds nucleons within atomic nuclei, constituting over 90% of visible matter in the universe. Nucleons—protons and neutrons—are composed of more fundamental quarks, with the strong interaction between quarks mediated by gluons. Under normal conditions, quarks and gluons are confined within hadrons, and free quarks and gluons have never been observed in nature—a phenomenon known as color confinement. By heating ordinary matter to extreme temperatures, one can overcome the strong interaction and liberate quarks and gluons from hadrons, creating a new state of matter consisting of deconfined quarks and gluons called Quark-Gluon Plasma (QGP) [1-3]. In the early universe, just tens of microseconds after the Big Bang, temperatures reached trillions of degrees, and QGP is predicted to have been the dominant form of matter during that epoch. As the universe expanded and cooled through complex phase transition processes, the QGP gradually transformed into ordinary hadronic matter, eventually forming the cosmos we observe today, including dense stellar objects like neutron stars. Therefore, studying the properties of QGP and its phase transitions is of fundamental importance for understanding cosmic evolution and the structure of visible matter.

In the 1970s, T.D. Lee [4] first proposed using large particle accelerators to accelerate heavy nuclei to near-light speeds, creating extreme temperature and density conditions through collisions that could deposit enormous energy in tiny volumes, potentially deconfining quarks and gluons to form QGP for laboratory study. Currently, the two major operating accelerators in high-energy physics are the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Through over two decades of dedicated experimental and theoretical efforts, analysis of heavy-ion collision data from these facilities has revealed multiple indirect signatures of QGP formation in relativistic heavy-ion collisions, including: (1) jet quenching, (2) constituent quark scaling of collective flow, and (3) J/ suppression [5-8]. Comparisons between experimental data and theoretical calculations show that this new form of matter has a shear viscosity-to-entropy ratio approaching the quantum limit, consistent with the properties of a strongly coupled ideal fluid.

Lattice QCD calculations from first principles indicate that at zero baryon chemical potential, the transition from hadronic matter to QGP is a smooth crossover. For larger baryon chemical potentials, lattice QCD calculations suffer from the sign problem, while effective QCD model calculations suggest a first-order phase transition [10-12], with the endpoint of this first-order transition boundary being a second-order phase transition point—the QCD Critical Point [8,10]. However, different theoretical models predict widely varying locations for the QCD critical point in the phase diagram, leaving its position highly uncertain. Experimentalists hope to identify signals of the QCD critical point and determine its location using sensitive observables in high-energy heavy-ion collisions.

RHIC consists of two 3.8 km circumference accelerator rings that accelerate heavy-ion beams to near-light speeds for collisions at interaction points. The STAR detector (Solenoidal Tracker at RHIC, [Figure 2: see original paper] [13]), located at the 6 o'clock position of the RHIC ring, is currently the only large particle detector still operating at RHIC. STAR comprises multiple sub-detectors with different functions, with its core being a cylindrical Time Projection Chamber (TPC) that measures charged particle momenta, ionization energy loss, and reconstructs particle tracks, enabling detection and identification of charged particles over a wide azimuthal angle and central rapidity region. The barrel region of the TPC is equipped with a Time-of-Flight (TOF) detector, which extends STAR's particle identification capabilities to high transverse momentum ranges and greatly enriches its physics program.

[Figure 1: see original paper] shows the QCD phase diagram [9], which describes how matter transitions between different phases under varying temperature, pressure, and other thermodynamic conditions. The phase diagram can be expressed in terms of temperature T and baryon chemical potential B. The green region represents hadronic matter, the yellow region represents quark-gluon plasma, the red-yellow dashed line indicates the chemical freeze-out line, the black solid line marks the first-order phase transition boundary, and the hollow square denotes the QCD critical point.

Over the past decade, while further investigating the properties of this strongly coupled QGP, extensive experimental and theoretical research has focused on the mechanism and thermodynamic conditions of phase transitions in hot and dense QCD matter—namely, the QCD phase structure. RHIC has completed two phases of its Beam Energy Scan program (2010-2014 and 2019-2021) , aiming to scan the QCD phase diagram by varying the collision energy of gold-gold collisions to change the system's temperature and baryon chemical potential, thereby searching for the QCD critical point and first-order phase transition boundary. The energy scan covers a center-of-mass energy per nucleon pair range of 3-200 GeV for gold-gold collisions (below 7.7 GeV using STAR's fixed-target mode), corresponding to baryon chemical potentials ranging from 20 MeV to as high as 750 MeV, enabling exploration of a wide region of the QCD phase diagram.

In high-energy heavy-ion collisions, the hot and dense QCD matter created expands and cools rapidly, allowing us to infer the properties of QCD matter and phase transition information only through observations of charged particles produced in the final state. When the system's thermodynamic state approaches the critical point, the correlation length increases and density fluctuations become enhanced, leading to critical phenomena such as critical opalescence observed when carbon dioxide is at its critical temperature. This review focuses on two sensitive observables used in STAR's Beam Energy Scan to search for the QCD critical point: higher-order moments of conserved charges [14] and light nuclei production yields [15-16]. Theoretical studies indicate that higher-order moments of conserved charges (such as net-charge, net-baryon, and net-strangeness) and light nuclei yield ratios are sensitive to the system's correlation length and neutron density fluctuations, respectively. Due to the influence of the QCD critical point, these observables should exhibit non-monotonic energy dependence, motivating experimental measurements across different collision energies to infer the existence of the QCD critical point.

Conserved Charge Fluctuations

1.1 Research Background

To search for the QCD critical point, theorists have proposed measuring higher-order fluctuations of conserved charges (such as net-charge, net-baryon, and net-strangeness) in heavy-ion collisions as probes [9,14,17-27], specifically the higher-order moments of conserved charge distributions on an event-by-event basis. Theoretical calculations show that near the critical point, the system's correlation length diverges, and higher-order cumulants of conserved charge distributions are particularly sensitive to this correlation length—for instance, the fourth-order cumulant scales with the seventh power of the correlation length.

Moreover, higher-order fluctuations of conserved charges are directly measurable quantities, with ratios of different orders directly related to theoretical susceptibilities. For example, the product of kurtosis and variance (σ^2) of a conserved charge distribution is closely related to the ratio of fourth-order to second-order susceptibilities ($_4/_2$). As the heavy-ion collision energy changes, the chemical freeze-out temperature and baryon chemical potential of the hot dense nuclear matter produced in the collisions also change (higher collision energy corresponds to higher temperature and lower baryon chemical potential), potentially traversing the critical region. As shown in Figure 3: see original paper, theoretical predictions indicate that when the system passes through the critical region, the fourth-order fluctuations of conserved charge distributions receive positive or negative contributions from critical fluctuations, displaying non-monotonic dependence on collision energy—a key signature for identifying the QCD critical point [17,21,26,28]. Higher-order cumulants of conserved charges serve as sensitive probes of the hot dense nuclear matter produced in high-energy heavy-ion collisions and are important tools for studying QCD phase transitions and searching for the QCD critical point. With data from RHIC's Beam Energy Scan, there is hope for breakthroughs in QCD phase diagram studies. However, it is important to note that these theoretical calculations assume a static system in thermal equilibrium with infinite volume, whereas heavy-ion collisions are dynamic, non-equilibrium systems with finite volume and rapid expansion. Therefore, developing dynamical models that incorporate a critical point represents both a hot topic and a major challenge in theoretical research.

On the other hand, while searching for signals of the QCD phase transition critical point experimentally, no experimental evidence has yet been observed for the smooth crossover between the QGP and hadronic phases at zero baryon chemical potential. Theoretical studies predict that if the chemical freeze-out temperature in heavy-ion collisions is sufficiently close to the chiral phase transition temperature, the sixth-order fluctuation of net-baryon number (C_6/C_2) will become negative [29]. Recent calculations based on effective QCD models [30] predict negative values for net-baryon number higher-order moments C_6/C_2 at collision energies s_{NN} > 7.7 GeV, though with relatively large uncertainties [32]. Additionally, lattice QCD calculations [33] also predict negative net-baryon number C_6/C_2 at collision energies s_{NN} > 39 GeV [34]. Therefore, measuring sixth-order and higher cumulants of conserved charges in experiments and comparing them with theoretical calculations can help identify signals of smooth crossover and QCD phase transitions in hot dense nuclear matter.

In recent years, based on RHIC Beam Energy Scan data, the STAR collaboration has published a series of experimental results on conserved charge cumulants [42-43]. Since electrically neutral hadrons are difficult to measure experimentally, net-baryon and net-strangeness numbers are typically approximated using net-proton and net-charged kaon numbers, respectively. The fourth-order cumulants of net-charge and net-charged kaon distributions measured in the 7.7-200 GeV energy range have large statistical uncertainties and show no clear energy dependence, requiring higher-precision measurements with more data. Recent STAR measurements of net-proton number distributions have revealed a non-monotonic energy dependence in the fourth-order cumulant, providing hints of a QCD critical point. However, the experimental measurements at lower energies (below 20 GeV) also suffer from large statistical uncertainties, as detailed in subsequent sections.

1.2 Observable Definitions

Let P(N) be the probability density distribution function, where N is the measured particle number. Defining $\delta N = N - \ N$ as the deviation of N from its mean value N , the r-th order central moment can be written as: $= \delta N$. The r-th order cumulant C can be expressed in terms of central moments as:

$C_1 = \ N$
$C_2 = \ \delta N^2 \ = {}_2$
$C_3 = \ \delta N^3 \ = {}_3$
$C_4 = \ \delta N^4 \ - 3 {}_2^{\,2} = {}_4 - 3 {}_2^{\,2}$
$C_5 = \ \delta N^5 \ - 10 {}_2 {}_3$
$C_6 = \ \delta N^6 \ - 15 {}_2 {}_4 - 10 {}_3^{\,2} + 30 {}_2^{\,3}$

Commonly used cumulants include the first- and second-order cumulants C_1 and C_2, which represent the mean (M) and width (variance σ^2) of a distribution. The normalized third- and fourth-order cumulants $C_3/(C_2)^3/^2$ and $C_4/{C_2}^2$ represent the skewness (S) and kurtosis ( ), respectively. In experimental analyses, to eliminate volume dependence and enable direct comparison with theoretical calculations, commonly used cumulant ratios include: $\sigma^2/M = C_2/C_1$, $S\sigma = C_3/C_2$, $\ \sigma^2 = C_4/C_2$, C_5/C_1, and C_6/C_2.

The experimental results presented here primarily use data from RHIC's first Beam Energy Scan program for gold-gold collisions at s_{NN} = 7.7-200 GeV, as well as gold-gold collision data at s_{NN} = 3 GeV collected during STAR's 2018 fixed-target run. In the experimental analysis, STAR's TPC and TOF detectors are primarily used to identify protons and antiprotons. Collision centrality—the radial distance between the centers of the two colliding gold nuclei—is characterized using the multiplicity of final-state charged particles. To suppress self-correlation effects from simultaneously measuring proton distributions [44], protons are excluded from the charged particles used for centrality determination. Since final-state charged particle multiplicity does not have a one-to-one correspondence with actual collision geometry, centrality width corrections are applied to net-proton cumulants to suppress volume fluctuation effects from using charged particle multiplicity for centrality selection. At low energies (3 GeV), centrality width corrections [44] cannot adequately suppress volume fluctuation effects due to the limited number of final-state charged particles available for centrality determination [45]. Recent studies suggest using wounded nucleon models for volume fluctuation corrections [46], though such approaches inevitably introduce model dependencies in experimental measurements. In fixed-target experiments, the finite thickness of the target nucleus leads to significant event pileup effects, where two or more collisions occur within extremely small spatial or temporal intervals that cannot be resolved by the detector's time and spatial resolution, causing them to be recorded as a single event containing particle information from multiple collisions. Therefore, pileup correction methods [47-48] are applied in the measurement of net-proton cumulants at 3 GeV. To account for the effects of finite detector efficiency on higher-order cumulant measurements, efficiency correction methods based on binomial distribution assumptions are applied in the cumulant calculations [49-51].

1.3 Experimental Results

This section presents recent experimental progress from the STAR collaboration on higher-order cumulant measurements of conserved charges.

[Figure 4: see original paper] shows the collision energy dependence of the fourth-order cumulant ratio C_4/C_2 for proton and net-proton distributions in central gold-gold collisions at RHIC-STAR for s_{NN} = 3-200 GeV [42-43]. The experimental acceptance covers rapidity |y| < 0.5 (0.5 < y < 0 at 3 GeV) and transverse momentum 0.4 < p_T (GeV/c) < 2.0. The measured C_4/C_2 for both protons and net-protons exhibits a non-monotonic energy dependence: it approaches unity at energies above 39 GeV, becomes significantly less than 1 at 19.6 GeV and 27 GeV, and exceeds 1 at the lower energy of 7.7 GeV. This non-monotonic behavior may indicate that the hot dense matter produced in the collisions passes through the critical region and is influenced by critical fluctuations. In contrast, hadronic transport model calculations (shown as light yellow bands) exhibit a monotonically decreasing trend from high to low energies. The experimental results are consistent with theoretical predictions of non-monotonic energy dependence as a signature of the QCD critical point, suggesting evidence for its existence. However, the experimental measurements of net-proton distributions below 20 GeV still have large statistical uncertainties and require higher-precision measurements. The results at 3 GeV and 2.4 GeV are from STAR fixed-target experiments and the HADES experiment at GSI Helmholtzzentrum für Schwerionenforschung, respectively, and are consistent within uncertainties. At 3 GeV, hadronic transport model UrQMD calculations (yellow crosses) without critical physics can reproduce STAR's measurements, indicating that this energy region is dominated by hadronic degrees of freedom. If a QCD critical region can be produced in heavy-ion collisions, it would only be accessible above 3 GeV.

STAR has recently completed measurements of higher-order net-proton cumulants beyond fourth order. [Figure 5: see original paper] shows the centrality dependence of the sixth-order fluctuation ratio C_6/C_2 for net-proton distributions in gold-gold collisions at s_{NN} = 27 GeV, 54.4 GeV, and 200 GeV [41]. The measurements cover transverse momentum 0.4 < p_T (GeV/c) < 2.0. The results show that C_6/C_2 becomes negative at 200 GeV starting from peripheral collisions (50%-60% centrality, N_{part} 40) and remains systematically negative in central collisions, while the results at 27 GeV and 54.4 GeV are consistent with zero within uncertainties from peripheral to central collisions. Lattice QCD predicts negative C_6/C_2 at temperatures around 160 MeV and baryon chemical potentials of 0-110 MeV. The 200 GeV experimental results in central collisions are qualitatively consistent with lattice QCD calculations, while hadronic transport model UrQMD calculations without critical physics are consistent with zero within uncertainties. This may represent an experimental signature of the smooth crossover between the QGP and hadronic phases at the high temperature and low baryon density produced in 200 GeV collisions, though current statistical uncertainties are large and the centrality bin is wide, requiring higher-precision measurements with more data in the future.

[Figure 6: see original paper] presents the collision energy dependence of higher-order net-proton cumulants C_4/C_2, C_5/C_1, and C_6/C_2 measured by STAR [52]. The analysis uses data from RHIC's first Beam Energy Scan for gold-gold collisions at s_{NN} = 7.7-200 GeV, with experimental acceptance covering mid-rapidity |y| < 0.5 and transverse momentum 0.4 < p_T (GeV/c) < 2.0. STAR measurements are shown as blue circles (0%-40% central collisions) and pink diamonds (50%-60% peripheral collisions). Calculations from lattice QCD, Functional Renormalization Group (FRG), UrQMD, and Hadron Resonance Gas (HRG) models are represented as bands and lines. Lattice QCD and FRG results incorporate QCD phase transition physics, while UrQMD and HRG calculations do not. C_5/C_1 in 0%-40% central collisions shows no clear energy dependence, fluctuating around zero within two standard deviations at all energies. In peripheral collisions, C_5/C_1 is positive and close to UrQMD and HRG calculations. C_6/C_2 becomes increasingly negative with decreasing energy in 0%-40% central collisions, while measured C_6/C_2 values in peripheral collisions are positive, qualitatively consistent with lattice QCD and FRG calculations that include QCD phase transition physics. The 3 GeV result shows a large value, primarily due to the wide 0%-40% centrality bin and significant volume fluctuation effects, though the measurement is qualitatively consistent with UrQMD calculations, supporting the conclusion that hadronic interactions dominate at this energy.

Experimentally, conserved charge fluctuations may be affected by non-critical effects unrelated to the QCD critical point, including baryon number conservation, baryon longitudinal transport, non-equilibrium effects, volume fluctuations, and final-state hadron decays and scattering. These background effects can be studied using theoretical models. Over more than a decade of RHIC-STAR measurements of conserved charge higher-order moments, the Chinese STAR group has made important contributions to data analysis and experimental methodology, developing effective methods for analyzing higher-order moments and extracting signals, including corrections for volume fluctuations, elimination of self-correlation effects, and detector efficiency corrections. These data analysis methods are crucial for obtaining precise experimental results. To enable high-precision higher-order cumulant measurements, BNL upgraded RHIC's electron cooling system and several STAR sub-detectors, including iTPC (inner Time Projection Chamber), EPD (Event Plane Detector), and ETOF (Endcap Time of Flight). The second phase of the Beam Energy Scan program was completed during 2019-2021, collecting massive datasets at multiple energies in both collider and fixed-target modes below 20 GeV. Data calibration and analysis are currently underway. Based on these data, measurements of conserved charge cumulants up to eighth order and non-diagonal higher-order cumulants such as baryon-strangeness correlations can be performed, providing additional sensitive observables for studying phase transitions in hot dense nuclear matter. The high-precision measurements from RHIC's second Beam Energy Scan will be a crucial step toward locating the QCD critical point and phase boundary.

Light Nuclei Production in Heavy-Ion Collisions

2.1 Research Background on Light Nuclei Production Mechanisms

Light nuclei, consisting of 2-40 nucleons, are relatively stable atomic nuclei also known as nuclear clusters. For over half a century, they have been important objects of study in intermediate-energy nuclear physics and high-energy heavy-ion collisions. Investigating these multi-nucleon systems and nucleon-nucleon interactions continuously tests our understanding of nuclear forces, nuclear structure, and rich nuclear physics phenomena. Studying light nuclei production in heavy-ion collisions provides deep insights into the behavior of nuclear matter under extreme conditions, such as the equation of state, nuclear astrophysics, nuclear symmetry energy, and QGP properties.

Recently, light nuclei yield ratios in heavy-ion collisions have been predicted to be sensitive probes for searching for the QCD critical point and first-order phase transitions [53-57]. Calculations based on nucleon coalescence models indicate that light nuclei production is directly related to local baryon number density fluctuations. The composite yield ratio $N_p \times N_t / N_d^2$ (where N_p is proton yield, N_d is deuteron yield, and N_t is triton yield) is proportional to neutron number density fluctuations in the system [56,58-59], making it a sensitive observable for detecting the QCD critical point and first-order phase transitions. While light nuclei yields are affected by many factors such as system volume and kinetic freeze-out temperature, making it difficult to isolate nucleon density fluctuations, the composite yield ratio $N_p \times N_t / N_d^2$ cancels out background effects from volume and temperature while preserving multi-nucleon correlation and fluctuation information, making nucleon number density fluctuations more observable [60-61].

Systematic measurements of light nuclei production in heavy-ion collisions can not only explore QCD phase structure but also provide detailed studies of light nuclei formation mechanisms. Current theoretical models for light nuclei production include nucleon coalescence models, statistical hadronization models, and dynamical models. In nucleon coalescence models, light nuclei have finite volumes, and when this volume becomes comparable to or larger than the system volume, light nuclei yields are suppressed, and the yield ratio $N_p \times N_t / N_d^2$ increases significantly as the system volume decreases—the so-called "light nuclei volume effect." In thermal models where light nuclei are treated as point particles, calculations show that composite yield ratios decrease with decreasing system volume. This means that measuring composite yield ratios in heavy-ion collisions can help distinguish between different production mechanisms. In lead-lead collisions at LHC energies, light nuclei yields and yield ratios are well described by statistical thermal models, which seems contradictory to the intuitive expectation that loosely bound light nuclei cannot survive at high temperatures, remaining an open puzzle. One possible explanation is that during the cooling and expansion stage of heavy-ion collisions, light nuclei reach detailed balance through scattering with surrounding hadrons, maintaining their yields. This hypothesis has been confirmed by Saha and rate equations as well as transport model calculations. However, recent kinetic calculations suggest that final-state hadron scattering suppresses yields of three-nucleon clusters like tritons and helium-3. These conflicting results and interpretations from different models require further clarification. In summary, systematic measurements of light nuclei yields in heavy-ion collisions can not only probe QCD phase structure but also provide valuable experimental constraints to validate different model calculations and enhance our understanding of light nuclei formation mechanisms. The following discussion focuses on STAR's measurements of triton production and the composite yield ratio $N_p \times N_t / N_d^2$ from RHIC's Beam Energy Scan.

2.2 RHIC-STAR Experimental Results

STAR has recently published mid-rapidity triton (t) transverse momentum spectra and yield measurements from RHIC's Beam Energy Scan. Combined with previously published proton and deuteron (d) spectra and mid-rapidity yields [63-67], these results enable studies of the centrality and energy dependence of the light nuclei composite yield ratio $N_p \times N_t / N_d^2$ for searching for the QCD critical point and first-order phase transition boundary [68]. It should be noted that the proton yields used in the composite ratio are primordial yields after subtracting contributions from weak decays of strange particles (dominated by Λ hyperons). The weak decay subtraction method uses Monte Carlo embedding techniques based on GEANT (for GEometry ANd Tracking) software to simulate the decay kinematics of strange particles across the full detector acceptance. A sample of strange particles is generated and embedded into real experimental data, and through GEANT simulation, the input strange particles decay into (anti)protons according to their decay channels and branching ratios, producing the decay (anti)proton spectrum. To obtain the final weak decay proton transverse momentum spectrum, the simulation must be normalized using strange particle yields measured by STAR [69-70]. The weak decay (anti)proton spectrum is then subtracted from the final-state (anti)proton spectrum to obtain the primordial (anti)proton spectrum.

[Figure 7: see original paper] shows the collision energy dependence of the fraction of weak decay (anti)protons in the total (anti)proton yield at mid-rapidity in 0%-10% central gold-gold collisions. The fraction of protons from weak decays increases monotonically with collision energy, rising from about 25% at 7.7 GeV to approximately 45% at 200 GeV. Theoretical calculations from the MUSIC+UrQMD model are consistent with these measurements, while the trend for antiprotons is opposite, decreasing monotonically with increasing energy.

[Figure 8: see original paper] shows the energy dependence of deuteron-to-primordial-proton and triton-to-primordial-proton yield ratios in 0%-10% central gold-gold collisions at mid-rapidity. Different symbols represent results from different experiments, and solid lines show statistical thermal model calculations with temperature and chemical potential parameters from the literature. Both ratios increase monotonically with decreasing collision energy, gradually converging. While the statistical thermal model qualitatively describes the energy dependence, it overestimates the triton-to-proton yield ratio, indicating that the underlying physics requires further investigation, possibly related to final-state hadron scattering during the system expansion.

As previously mentioned, the composite yield ratio N_p × N_t / N_d^2 is a sensitive probe of the QCD critical point. [Figure 9: see original paper] shows the charged particle multiplicity dependence of this composite yield ratio for gold-gold collisions at center-of-mass energies of 7.7-200 GeV. Each energy includes four centrality bins: 0%-10%, 10%-20%, 20%-40%, and 40%-80%, with 54.4 GeV additionally including 0%-20% centrality. The composite yield ratio decreases monotonically with increasing final-state charged particle multiplicity, and different energies show similar yield ratios at the same charged particle multiplicity, exhibiting a scaling behavior. The blue and yellow bands represent calculations from the hadronic transport model AMPT and the MUSIC+UrQMD hybrid model, respectively. MUSIC is a (3+1)-dimensional viscous hydrodynamics model that conserves energy, momentum, and baryon number, describing the dynamic evolution of QGP. To provide a reliable baseline for experimental measurements, neither the critical point nor first-order phase transition is included in AMPT and MUSIC+UrQMD calculations. Nucleons at kinetic freeze-out from these models are used to coalesce into light nuclei, and both models describe the measurements well. The light blue long-dashed line shows thermal model calculations at chemical freeze-out, which overestimates the experimental values by more than a factor of two at dN_{ch}/d   600. Theoretical calculations suggest this discrepancy may arise from hadronic rescattering during the expansion of hot dense nuclear matter, which suppresses yields of three-nucleon clusters like tritons and helium-3 by approximately 1.8 times relative to thermal model predictions [73]. However, this cannot explain the consistency between thermal model calculations and measurements in lead-lead collisions at LHC energies (s_{NN} = 2.76 TeV), requiring further study to resolve this difference. The black dashed line is a fit to the experimental data based on the nucleon coalescence model. In this model discussion, the fitting function assumes a thermally equilibrated static spherical Gaussian nucleon source:

$N\_p \times N\_t / N\_d^2 = p_0 \times (N\_t \times N\_p / N\_d^2) \times \exp[- (r\_d^2 + r\_t^2 - r\_p^2) / (2R^2)]$

where $R = p_1 \times$ (dN_{ch}/d)^(1/3) represents the radius of the spherical nucleon emission source; r_d = 1.96 fm and r_t = 1.59 fm are the root-mean-square nucleon radii of deuterons and tritons, respectively; and p_0 and p_1 are fitting parameters with best-fit values of 0.37 ± 0.008 and 0.75 ± 0.04, respectively. As shown in [Figure 9: see original paper], the ratio decreases monotonically with increasing final-state charged particle multiplicity and saturates at high multiplicity. At low multiplicity, the composite yield ratio is large because it is affected by the relative size of light nuclei radii and the system effective volume—only when light nuclei radii are smaller than the system effective volume does the yield ratio change significantly. The experimental data are well described by the nucleon coalescence formula, providing strong evidence for the nucleon coalescence formation mechanism of light nuclei in the RHIC energy region. Using the nucleon coalescence model fit as a baseline (shown in the lower panel of [Figure 9: see original paper]), significant enhancements are observed at 19.6 GeV and 27 GeV in 0%-10% central collisions, with deviations from the baseline reaching 4.1 standard deviations, while other data points deviate by less than two standard deviations. Notably, the 54.4 GeV result at 0%-20% centrality with similar dN_{ch}/d values falls on the fitted baseline. This suggests that the enhancement of the yield ratio at 19.6 GeV and 27 GeV in 0%-10% central collisions is primarily due to different baryon chemical potentials rather than system volume effects. However, whether this enhancement originates from critical behavior or a first-order phase transition in hot dense nuclear matter requires further high-precision experimental measurements and more theoretical calculations using realistic equations of state for heavy-ion collisions.

[Figure 10: see original paper] shows the energy dependence of the composite yield ratio in central (0%-10%) and peripheral (40%-80%) gold-gold collisions. For comparison, the dashed lines represent the fits to the dN_{ch}/d dependence from [Figure 9: see original paper]. Results from the hadronic transport model AMPT and the MUSIC+UrQMD hybrid model are also shown. For 0%-10% central collisions, the deviations from the nucleon coalescence baseline at 19.6 GeV and 27 GeV are significant at the 4.1σ level. Panel (a) shows the composite yield ratio for different common transverse momentum acceptance ranges for primordial protons, deuterons, and tritons, revealing that the significance of the deviation from the baseline decreases with reduced transverse momentum acceptance, indicating that the enhancement has transverse momentum acceptance dependence. Panel (b) shows the energy dependence in peripheral collisions, where measurements are well described by the coalescence model baseline, while AMPT and MUSIC+UrQMD calculations describe the energy dependence trend but overestimate the results. The non-monotonic energy dependence of the composite yield ratio in 0%-10% central collisions remains a topic of great interest and will stimulate further experimental and theoretical investigations to determine whether it originates from critical fluctuations or a first-order phase transition in heavy-ion collisions.

Light nuclei, as products of heavy-ion collisions, have complex formation mechanisms and evolution processes that remain important physics questions of interest. On one hand, discrepancies between statistical thermal model calculations and STAR measurements will trigger further exploration and consideration of light nuclei formation mechanisms in heavy-ion collisions, while experimental results provide additional constraints for theoretical studies. On the other hand, the composite yield ratio of light nuclei is predicted to probe local neutron number density fluctuations, extracting information carried by final-state light nuclei during phase transitions in hot dense nuclear matter and providing a new approach for exploring QCD phase diagram structure. The observed non-monotonic energy dependence of the composite yield ratio in 0%-10% central gold-gold collisions will drive further experimental and theoretical research.

Conclusion and Outlook

Results from RHIC's first Beam Energy Scan have revealed hints of a QCD critical point, but the observations still have large uncertainties that prevent definitive confirmation of its existence. To improve experimental precision, Brookhaven National Laboratory upgraded RHIC's beam cooling system to provide higher luminosity at lower energies, increasing event rates. Additionally, the STAR collaboration upgraded several detectors, including the inner TPC for improved track reconstruction, endcap TOF detectors, and an event plane detector. STAR has now completed data collection for the second Beam Energy Scan at multiple energies in both collider and fixed-target modes , with data calibration and physics analysis actively underway, promising more accurate experimental insights into the QCD phase diagram.

To explore the high baryon density region of the QCD phase diagram and investigate nuclear matter phase structure, major new particle accelerator and detector facilities are being built and operated worldwide [Figure 11: see original paper]. These include the Compressed Baryonic Matter experiment at FAIR (Facility for Antiproton and Ion Research) in Germany, the J-PARC (Japan Proton Accelerator Research Complex) experiment, the NICA (Nuclotron-based Ion Collider Facility) experiment at the Joint Institute for Nuclear Research in Dubna, Russia, the CEE (HIRFL-CSR External-target) experiment at the Institute of Modern Physics in China, and the HIAF (High Intensity Heavy-ion Accelerator Facility) to be built in Huizhou, Guangdong, China by 2025 [74]. These experiments will cover different energy regions and provide important impetus for studying the phase structure of nuclear matter at high baryon density, promising major advances in the future and further expanding our understanding of the fundamental structure of matter.

Author Contributions

ZHANG Yu drafted the initial manuscript for the "Conserved Charge Higher-Order Moments" section; ZHANG Dingwei drafted the initial manuscript for the

"Light Nuclei Production" section; LUO Xiaofeng conceived the overall structure and outline, drafted the introduction and conclusion sections, and reviewed and revised the entire manuscript. All authors have reviewed the final version and agree with its content.

References

[References are preserved exactly as in the original text]

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