# Production of light nuclei in Au+Au collisions at STAR

Rishabh Sharma • (for the STAR Collaboration) rishabhsharma@students.iisertirupati.ac.in

<sup>a</sup>Department of Physics, Indian Institute of Science Education and Research (IISER) Tirupati, Tirupati, 517619, Andhra Pradesh, India

## 4 Abstract

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The Beam Energy Scan (BES) program at RHIC explores the QCD phase 5 diagram by varying collision energy in heavy-ion collisions. Lattice QCD cal-6 culations predict a smooth crossover between the hadronic medium and the 7 Quark-Gluon Plasma (QGP) at high temperatures and low baryon chemical 8 potential, while several QCD-based models suggest a first-order phase transi-9 tion at lower temperatures and higher baryon chemical potential, indicating 10 a possible critical point. In the coalescence model, light nuclei, as loosely 11 bound clusters of baryons, are thought to form via final-state coalescence of 12 nucleons and might be sensitive to baryon density fluctuations, making them 13 valuable probes for QCD critical phenomena. 14

In these proceedings, we present the energy and centrality dependence of transverse momentum spectra, yields, and ratios of light nuclei (p, d, and t)in Au+Au collisions at  $\sqrt{s_{NN}} = 7.7-200$  GeV from the BES-I dataset. These observables offer insights into the production mechanisms of light nuclei and may help explore signatures related to critical phenomena.

## 20 1. Introduction

The primary goal of the Beam Energy Scan (BES) program at the Rela-21 tivistic Heavy Ion Collider (RHIC), conducted by the STAR Collaboration, is 22 to investigate the structure of the Quantum Chromodynamics (QCD) phase 23 diagram. Lattice QCD calculations suggest a smooth crossover transition 24 between hadronic matter and the Quark-Gluon Plasma (QGP) at vanishing 25 baryon chemical potential ( $\mu_B = 0 \text{ MeV}$ ) [1]. Several QCD-based models pre-26 dict the existence of a critical point, beyond which the transition becomes 27 first-order at higher  $\mu_B$  [2, 3]. The BES program aims to experimentally 28

explore signatures of such critical phenomena within the conjectured QCD
phase diagram [4].

Light nuclei such as deuterons (d) and tritons (t) are abundantly produced 31 in relativistic heavy-ion collisions, yet their production mechanisms remain 32 under debate. Due to their low binding energies (of the order of a few MeV), 33 these nuclei are unlikely to survive the hot and dense hadronic medium, where 34 temperatures far exceed their binding energies. Instead, they are thought 35 to break apart in the hadronic phase and re-form later via coalescence of 36 nucleons close in phase space [5, 6]. Studying their production thus offers 37 insight into nucleon distributions at kinetic freeze-out, and provides valuable 38 information about the properties of nuclear matter at high energy densities. 39 Within the coalescence framework, the yield ratio  $N(t) \times N(p)/N^2(d)$  has 40 been proposed as a probe sensitive to neutron density fluctuations  $\Delta n$  [7]: 41

$$\frac{N(t) \times N(p)}{N^2(d)} = \frac{1}{2\sqrt{3}} (1 + \Delta n), \tag{1}$$

where  $\Delta n = \langle (\delta n)^2 \rangle / \langle n \rangle^2$ , with  $\langle n \rangle$  representing the average neutron density and  $\delta n$  its local fluctuation.

Therefore, measuring light nuclei yields and their ratios not only helps to understand their production mechanism in heavy-ion collisions but may also provide a probe to critical phenomena in the QCD phase diagram.

#### 47 2. Results and Discussions

#### 48 2.1. Transverse Momentum Spectra

The data presented in these proceedings are from Au+Au collisions at  $\sqrt{s_{NN}} = 7.7, 14.5, 19.6, 27, 39, 54.4, and 200 GeV, collected by the STAR$ experiment [8, 9]. Light nuclei identification was performed using the TimeProjection Chamber (TPC) [10] and the Time-of-Flight (TOF) [11] detector.The TPC identifies particles via their specific ionization energy loss <math>(dE/dx)in a gaseous medium, while the TOF detector provides mass-squared  $(m^2)$ measurements based on the time of flight of the particle.

Figure 1 shows the transverse momentum  $(p_T)$  spectra of p, d, and tat mid-rapidity for various centrality classes in Au+Au collisions across the BES energies. The proton spectra has been corrected for the contribution from weak decays by a data drive method [9]. The dashed lines represent Blast-Wave fits to the data. A clear  $p_T$  dependence is observed for all particle species.



Figure 1: Transverse momentum spectra of (a) primordial p (|y| < 0.1) (b) d (|y| < 0.3), and (c) t (|y| < 0.5) in various centrality classes of Au+Au collisions at  $\sqrt{s_{NN}} = 7.7 - 200$  GeV. The vertical lines and boxes on each data point indicate statistical and systematic uncertainties, respectively. Figure taken from [8, 9].



Figure 2: Centrality dependence of  $\langle p_T \rangle$  and dN/dy (normalized by  $0.5 \langle N_{part} \rangle$ ) of d and  $\bar{d}$  in Au+Au collisions at  $\sqrt{s_{NN}} = 7.7 - 200$  GeV. The vertical lines and boxes on each data point indicate statistical and systematic uncertainties, respectively. Figure taken from [8].

### 62 2.2. $p_T$ -integrated yields and $\langle p_T \rangle$

The  $p_T$ -integrated yields (dN/dy) and average  $p_T$   $(\langle p_T \rangle)$  are obtained by combining the measured  $p_T$  region with extrapolations to the unmeasured regions using individual Blast-Wave fits.

Figure 2 shows the energy and centrality dependence of  $\langle p_T \rangle$  and dN/dy(normalized by  $0.5 \langle N_{part} \rangle$ ) of d and  $\bar{d}$  with  $\langle N_{part} \rangle$  in Au+Au collisions across BES energies, where  $\langle N_{part} \rangle$  is the mean value of the number of participants in a given centrality class.

A decreasing trend in the dN/dy of d is observed from 7.7 to 200 GeV, indicating that baryon stopping plays a more significant role than pair production at lower center-of-mass energies. In contrast, the dN/dy of  $\bar{d}$  increases with energy. This is due to pair production becoming more dominant at higher center-of-mass energies, which leads to more anti-nucleons available for  $\bar{d}$  formation.

Furthermore,  $\langle p_T \rangle$  increases from peripheral to central collisions. A slight increasing trend is also observed as a function of collision energy albeit with large uncertainties. These features suggest that the radial flow grows with collision centrality. The dN/dy and  $\langle p_T \rangle$  of t exhibit similar trends as those observed for d [9].

#### <sup>81</sup> 2.3. Yield ratio of light nuclei

Figure 3 shows the dependence of the yield ratio  $N(t) \times N(p)/N^2(d)$ on charged-particle multiplicity  $(dN_{\rm ch}/d\eta)$  in Au+Au collisions across BES



Figure 3:  $N(t) \times N(p)/N^2(d)$  as a function of  $dN_{\rm ch}/d\eta$  in 0-10%, 10-20%, 20-40%, and 40-80% centrality of Au+Au collisions at  $\sqrt{s_{NN}} = 7.7 - 200$  GeV. The vertical lines and brackets on each data point indicate statistical and systematic uncertainties, respectively. Figure taken from [9].

energies. The ratio is observed to decrease with increasing  $dN_{\rm ch}/d\eta$  and exhibits a scaling behavior. The shaded bands represent calculations from the transport AMPT and MUSIC+UrQMD hybrid models, which do not include a critical point or first-order phase transition [12]. These serve as a baseline and reproduce the overall trend of the experimental data.

The dashed line is the thermal model calculation at chemical freeze-out 89 for central Au+Au collisions [13]. Thermal model is observed to overestimate 90 the measured experimental yield ratios. The dot-dashed line is a fit based on 91 the assumption of a thermally equilibrated and static nucleon source within 92 the coalescence model [12]. Using this fit as a reference, the lower panel 93 of Figure 3 shows deviations from the baseline. While most data points lie 94 within  $2\sigma$  of the fit, an enhancement is observed in the 0–10% most central 95 Au+Au collisions at  $\sqrt{s_{NN}} = 19.6$  and 27 GeV, with a combined significance 96 of 4.1 $\sigma$ . In contrast, the yield ratio for 0–20% central Au+Au collisions at 97  $\sqrt{s_{NN}} = 54.4 \text{ GeV}$ , which corresponds to a similar  $dN_{\rm ch}/d\eta$ , agrees well with 98 the coalescence baseline and shows no such enhancement. This suggests that 99 the observed enhancement may be related to baryon density fluctuations 100 than to the overall system size. 101

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Additionally, the significance of the enhancement decreases when a nar-

<sup>103</sup> rower common  $p_T$  range is used for the extraction of the dN/dy of p, d, and <sup>104</sup> t, indicating a possible  $p_T$ -dependence in the observed signal. Yield ratios <sup>105</sup> in peripheral Au+Au collisions are in good agreement with the coalescence <sup>106</sup> baseline within uncertainties, however, predictions from the AMPT and MU-<sup>107</sup> SIC + UrQMD calculations tend to overestimate the measured data [9].

#### 108 3. Summary

We report the  $p_T$ -spectra, integrated yields (dN/dy), and average  $p_T$ ( $\langle p_T \rangle$ ) of  $(d, \bar{d}, \text{ and } t)$  in Au+Au collisions at  $\sqrt{s_{NN}} = 7.7-200$  GeV. The dN/dy of d and t decreases with energy due to the reduced baryon stopping at higher  $\sqrt{s_{NN}}$ , while  $\bar{d}$  yields increase due to enhanced pair production. The  $\langle p_T \rangle$  values rise with both collision centrality and energy, indicating stronger radial flow in larger and more energetic systems.

The yield ratio  $N(t) \times N(p)/N^2(d)$ , which is suggested to be sensitive to 115 baryon density fluctuations, shows a scaling behavior with charged-particle 116 multiplicity. While most data points follow the expected coalescence trend, 117 an enhancement is observed in central Au+Au collisions at  $\sqrt{s_{NN}} = 19.6$  and 118 27 GeV, with a combined significance of  $4.1\sigma$ . This enhancement is not seen 119 in central Au+Au collisions  $\sqrt{s_{NN}} = 54.4$  GeV, despite similar multiplicity, 120 suggesting that the effect is driven by baryon density fluctuations rather 121 than system size. The observed deviations may offer insights into critical 122 phenomena in the QCD phase diagram. 123

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