3^A_H and 4^A_H Lifetime, Yield, Directed Flow Measurements in Au+Au Collisions at \( \sqrt{s_{NN}} = 3 \) GeV With the STAR Detector

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Abstract. In this proceedings, the lifetime and yields of 3^A_H and 4^A_H in Au+Au collisions at \( \sqrt{s_{NN}} = 3 \) GeV are presented. The measured yields are compared to measurements at other energies and theoretical models, and the physics implications are discussed. We also report the first observation of the 3^A_H and 4^A_H directed flow in 5 - 40% centrality. The directed flow of 3^A_H and 4^A_H are compared with those of the copiously produced particles such as p, \( \Lambda \), d, t, 3^He, and 4^He. These results shed light on light hyper-nuclei production in heavy-ion collisions in the high baryon density region.

1 Introduction

As is known to all, the normal nucleus is made up of protons and neutrons. When a nucleon is replaced by a \( \Lambda \) hyperon (\( S = -1 \). Here \( S \) denotes the quantum number of strangeness), the nucleus is transformed into a hyper-nucleus which allows us to study the hyperon-nucleon (Y-N) interaction. It is well known that 2-body and 3-body Y-N interactions, especially at high baryon density, are essential for understanding the inner structure of compact stars [1-2]. Measurements of the lifetime, binding energy, decay branching ratios of hyper-nuclei can give us important information on Y-N interaction.

Anisotropic flow has been commonly used for studying the properties of matter created in high energy nuclear collisions, due to its genuine sensitivity on early stage collision dynamics [3]. The first order coefficient of the Fourier-expansion of azimuthal distribution, known as directed flow (\( v_1 \)), has been analyzed for all particles ranging from the lightest pion-mesons to light nuclei in such collisions [4-5].

In this proceedings, the lifetime, yields and directed flow of 3^A_H and 4^A_H in Au+Au collisions at \( \sqrt{s_{NN}} = 3 \) GeV will be discussed. The data was collected by the STAR experiment at RHIC with the fixed-target (FXT) setup. The gold beam of 3.85 GeV/u is collided on a thin gold target with 1% interaction probability, located at 200 cm along the beam direction from the center of the STAR Time-Projection Chamber (TPC). A total of 260M good minimum bias (MB) events were selected for this analysis.

2 Data Analysis, Results and Discussion

At the \( \sqrt{s_{NN}} = 3 \) GeV collisions, the first order event plane is determined by the Event Plane Detector (EPD) [6], which is designed to measure the pattern of forward-going charged

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particles emitted in heavy-ion collisions and covers a pseudorapidity range of $2.14 < \eta < 5.09$. The directed flow ($v_1$) discussed below is determined by the first order event plane.

2.1 Particle Reconstruction

The hyper-nuclei $^3\Lambda H$ and $^4\Lambda H$ are reconstructed with following decay channels: $^3\Lambda H \rightarrow ^3\text{He} + \pi^-\Lambda, ^4\Lambda H \rightarrow ^4\text{He} + \pi^-\Lambda$. To assure the quality of each track, a minimum of 15 hits out of 45 hits in the TPC is required. The secondary decay topology is reconstructed by the KFParticle program which is based on a Kalman filter method [7]. In the program, the error-matrices are used to enhance the reconstruction significance. A set of cuts on topological variables are applied to the hyper-nuclei candidates to optimize the significance.

2.2 $^3\Lambda H$ and $^4\Lambda H$ Lifetime Measurements

The reconstructed $^3\Lambda H$ and $^4\Lambda H$ candidates are divided into different $L/\beta\gamma$ intervals, where $L$ is the decay length, $\beta$ and $\gamma$ are particle velocity and Lorentz factor, respectively. The raw signal counts $N_{raw}$ for each $L/\beta\gamma$ interval are obtained from corresponding background-subtracted invariant mass spectrum using a bin counting method. The signal counts are corrected with the detector acceptance and reconstruction efficiency ($\varepsilon_{TPC} \times \varepsilon_{PID}$). The corrected hyper-nuclei counts as a function of $L/\beta\gamma$ is fitted to an exponential function ($N = N_0 e^{-L/\beta\gamma\tau}$) to obtain the mean lifetime $\tau$.

The lifetimes $232 \pm 29(\text{stat.}) \pm 37(\text{syst.})$ for $^3\Lambda H$ (2-body decay channel) and $218 \pm 8(\text{stat.}) \pm 12(\text{syst.})$ for $^4\Lambda H$ are obtained from the $\sqrt{s_{NN}} = 3$ GeV data. As shown in Fig. 1, the $^4\Lambda H$ measurement is the most precise measurement to date, and within uncertainties, the measured $^3\Lambda H$ and $^4\Lambda H$ lifetimes are consistent with previous measurements from ALICE [8, 9], STAR [10], HypHI [11].

![Figure 1. Measured lifetimes of $^3\Lambda H$ (a) and $^4\Lambda H$ (b) are shown comparing to previous measurements and theoretical calculations as well as the free $\Lambda$ lifetime. The experimental average lifetimes and the corresponding uncertainty of $^3\Lambda H$ and $^4\Lambda H$ are also shown as orange bands.](image)

2.3 $^3\Lambda H$ and $^4\Lambda H$ Yield Measurements

The hyper-nuclei $^3\Lambda H$ and $^4\Lambda H$ yields from their 2-body decay channels are extracted as a function of $p_T$ and $y$ in two centrality selections: 0–10% and 10–50%. The efficiency-corrected $p_T$ spectra in each rapidity slice are extrapolated down to $p_T=0$ to obtain $p_T$ integrated value of yields ($dN/dy$). Different functions (e.g blast-wave function) are used to estimate the systematic uncertainties in the unmeasured $p_T$ regions. We have assumed branching ratios of 25% and 50% for the 2-body decay of $^3\Lambda H$ and $^4\Lambda H$, respectively.

The $^3\Lambda H$ and $^4\Lambda H$ yields at $|y| < 0.5$ as a function of beam energy in central heavy-ion collisions are extracted and are compared to theoretical models as shown in Fig. 2. For $^3\Lambda H$, the measured yield is consistent with the thermal model from GSI/Heidelberg [12]. The thermal model adopting the canonical ensemble can approximately describe the $^3\Lambda H$ yield
both at 3 GeV and 2.76 TeV. Canonical ensemble thermal statistics is required to account for the large \( \phi/K^- \) and \( \phi/\Xi^- \) ratios measured at the same energy as well. We also observe that the coalescence model (DCM) [13] is consistent with the \(^3\Lambda H\) yield while underestimating the \(^4\Lambda H\). On the other hand, the hybrid UrQMD overestimates both \(^3\Lambda H\) and \(^4\Lambda H\) yields by an order of magnitude.

### 2.4 \(^3\Lambda H\) and \(^4\Lambda H\) Directed Flow Measurements

Directed flow of \( \Lambda \) hyperons, \(^3\Lambda H\), and \(^4\Lambda H\) are extracted with event plane method. Figure 3 shows the \( v_1 \) for hyper-nuclei and \( \Lambda \) hyperons versus rapidity from the \( \sqrt{s_{NN}} = 3 \text{ GeV} \) Au + Au collisions. The yellow-red line is the result of linear fit to the data and is plotted in full rapidity region \( |y| \leq 0.9 \). For comparison, the \( v_1 \) distributions for \( p, d, t, ^3\text{He} \) and \( ^4\text{He} \), from the events with same centrality, are shown as open symbols in the figure. Here the results of the linear fits to the light-nuclei are plotted as dashed-lines only in the positive rapidity region. As one can see, the \( v_1 \) of \( \Lambda \) hyperons is consistent with that of protons, and the slopes of hyper-nuclei \( v_1 \) are also similar to that of the corresponding light-nuclei with the same mass number within statistical uncertainties.

![Figure 3. Hyper-nuclei \( v_1 \) as a function of rapidity from the \( \sqrt{s_{NN}} = 3 \text{ GeV} \) 5 – 40\% mid-central Au + Au collisions at RHIC-STAR. In case of \(^3\Lambda H\), both 2-body (dots) and 3-body (triangles) decays are used. Results from fitting with a first-order polynomial function are shown as the yellow-red lines. The rapidity dependence of \( v_1 \) for \( p, d, t, ^3\text{He} \) and \( ^4\text{He} \) are also shown as open-circles, diamonds, up-triangles, down-triangles and squares, respectively. The corresponding results of the linear fits are shown as dashed lines in the positive rapidity region.](image)

Extracted mid-rapidity \( v_1 \) slopes, \( dv_1/dy|_{y=0} \), for \( \Lambda \) hyperons, \(^3\Lambda H\), and \(^4\Lambda H\), are summarized in Fig. 4 as red filled-squares, as a function of particle mass. For comparison, the slopes of light-nuclei \( p, d, t, ^3\text{He} \), and \( ^4\text{He} \) from the events with same centrality class (5-40\%) in \( \sqrt{s_{NN}} = 3 \text{ GeV} \) Au+Au collisions are shown as open circles. The result of a linear fit to the light-nuclei is shown as the yellow-red line in the figure. Overall, hyper-nuclei \( v_1 \) slopes are consistent with that of light-nuclei which has similar mass albeit the large uncertainties in the results. The mass dependence of the \( v_1 \) slope implies that the coalescence is the dominant mechanism for hyper-nuclei production in heavy-ion collisions.
3 Summary

In summary, we reconstruct the light hyper-nuclei $^3\Lambda$H and $^4\Lambda$H from $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at RHIC-STAR. Lifetimes of $^3\Lambda$H and $^4\Lambda$H from their 2-body decay channel are measured to be $232 \pm 29$ (stat.) $\pm 37$ (syst.) and $218 \pm 8$ (stat.) $\pm 12$ (syst.) respectively. The $^3\Lambda$H and $^4\Lambda$H lifetimes are consistent with previous measurements and theoretical calculations. Meanwhile, the hyper-nuclei $^3\Lambda$H and $^4\Lambda$H yields at $|y| < 0.5$ as a function of beam energy in central heavy-ion collisions are reported and compared to theoretical models. We also reported the first observation of $^3\Lambda$H and $^4\Lambda$H directed flow $v_1$ from mid-central (5-40%) collisions. The rapidity dependence of their $v_1$ are compared with that of $\Lambda$ hyperon and light nuclei p, d, t, $^3$He and $^4$He from the collisions with the same centrality class. It is found that, within statistical uncertainties, the mid-rapidity $v_1$ slope of $^3\Lambda$H and $^4\Lambda$H are similar to those of light nuclei with the similar mass, such as t, $^3$He, and $^4$He. In other words, they seem to follow the baryon mass scaling. These observations imply that coalescence of nucleons and $\Lambda$ hyperons is the dominant mechanism for the light hyper-nuclei production in such collisions.

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References