Recent Studies on Hypernuclei Lifetimes from STAR

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Abstract. The hyperon-nucleon (Y-N) interaction is an essential ingredient in the description of the equation-of-state of high-baryon-density matter. Light hypernuclei ($A = 3, 4$), being simple Y-N bound states, serve as cornerstones of our understanding of the Y-N interaction. Thus, precise measurements of their lifetimes are important, as they provide stringent tests to hyperon-nucleon interaction models.
The yields of light hypernuclei are expected to increase from high to low energy heavy-ion collisions due to the increase in baryon density. As a result, the STAR Beam Energy Scan II program, which spans an energy range of $\sqrt{s_{NN}} = 3.0 - 27.0$ GeV, is particularly suited for hypernuclei studies. In these proceedings, recent results on the lifetimes of light hypernuclei (${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He) measured in $\sqrt{s_{NN}} = 3.0$ and 7.2 GeV Au+Au collisions are presented. The relative branching ratio R_3 of the ${}^{3}_{\Lambda}$H is intimately related to its lifetime. A new R_3 measurement using data from $\sqrt{s_{NN}} = 3.0$ GeV Au+Au collisions is reported. These results will be compared to previous measurements and theoretical calculations, and the physics implications will be discussed.

1 Introduction

Hypernuclei are nuclei containing at least one hyperon. They serve as important experimental probes to access the hyperon-nucleon (Y-N) interaction, which is an important component in the equation-of-state of high-baryon-density matter, such as neutron stars. Measurements of the lifetimes and binding energies of hypernuclei provide tests for hyperon-nucleon interaction models. In particular, the hypertriton, ${}^{3}_{\Lambda}$H, the lightest known hypernuclei, has a small binding energy ($B_{\Lambda} \sim O(0.1$ MeV)). Due to its loosely bounded nature, it is believed that the ${}^{3}_{\Lambda}$H lifetime $\tau({}^{3}_{\Lambda}\mathrm{H})$ is very close to the free Λ lifetime $\tau(\Lambda)$, 263 ± 2 ps [1]. Recently, STAR, ALICE and HypHI have reported ${}^{3}_{\Lambda}$H lifetimes ranging from $\sim 50\%$ to $\sim 100\%$ of $\tau(\Lambda)$ with large uncertainties. This situation calls for more precise measurements of the ${}^{3}_{\Lambda}$H lifetime to clarify the situation.

2 Hypernuclei Reconstruction with the STAR Detector

In heavy-ion collisions, hypernuclei yields are expected to increase towards lower beam energies due to the increasing baryon density [2]. The STAR Beam Energy Scan II program

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(BES-II), which covers collision energies from $\sqrt{s_{NN}}$ = 3.0 to 27.0 GeV, provides a great opportunity for studies of light hypernuclei.

At STAR, hypernuclei are reconstructed using their mesonic decay channels, e.g. ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$, ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$. Particle identification of the daughter tracks is achieved by the measured ionization energy loss in the Time Projection Chamber (TPC). The KFParticle package [3], based on the Kalman Filter method, is utilized to reconstruct hypernuclei candidates from their daughter tracks. The combinatorial background is estimated via event mixing or rotating all daughter pion candidates within one event [4]. In the following, we will discuss recent hypernuclei lifetime and relative branching ratio results from STAR.

3 Hypernuclei Lifetimes

3.1 Measurements from BES-II

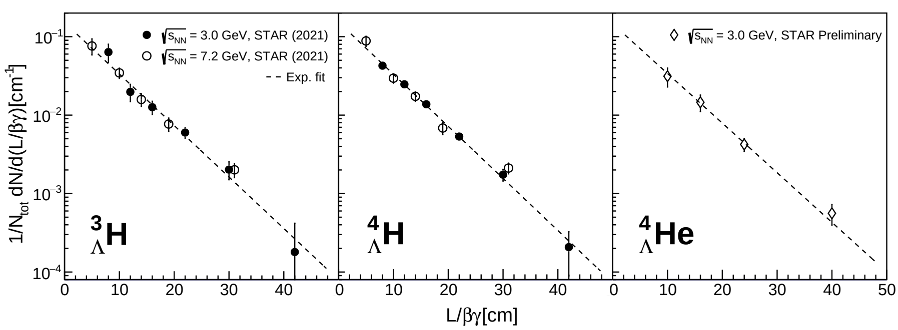

Figure 1. The normalized yield versus the proper decay length $L/\beta\gamma$ for ${}^{3}_{\Lambda}$H (left panel), ${}^{4}_{\Lambda}$H (middle panel), and ${}^{4}_{\Lambda}$He (right panel). The dotted lines represent exponential fits to the data.

In 2018, data from Au+Au collisions at $\sqrt{s_{NN}}$ = 3.0 GeV and 7.2 GeV have been collected, with 258 and 155 million recorded events respectively. The lifetime analyses were carried out for ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H using both data sets, while the ${}^{4}_{\Lambda}$He analysis utilized the $\sqrt{s_{NN}}$ = 3.0 GeV dataset only. In order to extract the lifetime, the hypernuclei yields are measured as a function of proper decay length. As shown in Fig. 1, the resultant distributions are well described by exponential functions.

The lifetimes are extracted via χ^2 fits with exponential functions. As a cross-check, the lifetime of the Λ is extracted using the same method and the measured lifetime, $267 \pm 1(stat) \pm 4(syst)$ ps, is consistent with the PDG value [1]. Four major sources of systematic uncertainties are considered. They include imperfect description of topological variables in the GEANT simulations for efficiency estimation, imperfect knowledge of the true kinematic distribution of the hypernuclei, the simulated TPC tracking efficiency, and the signal extraction technique. Their contributions are estimated by varying topological cuts for hypernuclei candidate selection, the hypernuclei transverse montentum p_T and rapidity y distributions in the GEANT simulations, the TPC track quality selection criteria, and the background subtraction method. Other effects, such as particle misidentification, contamination from three-body decays, and coulomb dissociation through target material, have been quantified via Monte-Carlo simulations and are negligible compared to other sources of uncertainty. Different sources of systematic uncertainties are assumed to be uncorrelated and

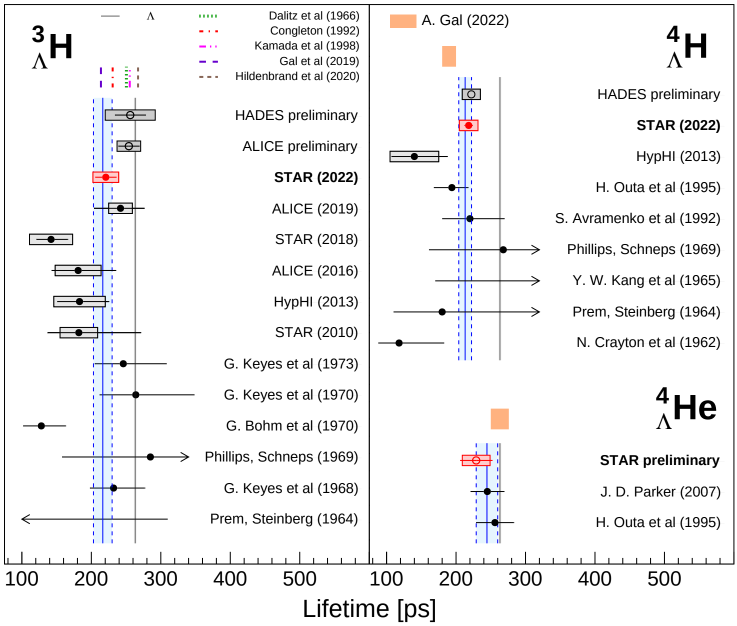

Figure 2. Compilation of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He lifetimes. The experimental average lifetimes are indicated by blue shaded bands. The short dashed lines and solid bands represent theoretical calculations while the solid grey line indicates the free Λ lifetime.

added in quadrature. The total systematic uncertainty amounts to 8.2%, 6.0%, and 8.7% for $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, and $^{4}_{\Lambda}$He respectively.

The $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, and $^{4}_{\Lambda}$He lifetimes are measured to be $221 \pm 15(stat) \pm 19(syst)$ ps, $218 \pm 6(stat) \pm 13(syst)$ ps [5], and $229 \pm 23(stat) \pm 20(syst)$ ps respectively. In Fig. 2, the results are compared to published measurements, preliminary results from ALICE [6] and HADES [7], and theoretical calculations. The experimentally averaged $^{3}_{\Lambda}$H lifetime is $(82 \pm 5)\%$ of the Λ lifetime, consistent with theoretical calculations incorporating pion final-state interactions [8]. Similar to the $^{3}_{\Lambda}$H, the experimental averages of $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He lie below the Λ lifetime. Their ratio $\tau_{avg}(^{4}_{\Lambda}\mathrm{H})/\tau_{\mathrm{avg}}(^{4}_{\Lambda}\mathrm{He})$ is equal to 0.85 ± 0.07, compatible with theoretical estimates invoking the isospin rule [9], which is based on the experimentally measured ratio, $\Gamma(\Lambda \to n + \pi^0)/\Gamma(\Lambda \to p + \pi^-) \approx 0.5$. The new $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H results from STAR have an improved precision compared to previous measurements, providing stronger constraints to hyperon-nucleon interaction models.

4 Relative Branching Ratio of the Hypertriton

The $^{3}_{\Lambda}$H relative branching ratio R_3, defined as:

$$R_3 = \frac{BR(^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-)}{BR(^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-) + \mathrm{BR}(^{3}_{\Lambda}\mathrm{H} \to \mathrm{d} + \mathrm{p} + \pi^-)}, \tag{1}$$

where *BR* stands for branching ratio, is an important input to theoretical computations of the $^{3}_{\Lambda}$H lifetime. Calculations has shown that the two-body and three-body mesonic decay channels of the $^{3}_{\Lambda}$H contribute $\sim 97\%$ of the total decay rate [10], while the remaining $\sim 3\%$

stems from four-body mesonic decays and non-mesonic decays. Since the π^- decay rate and the π^0 decay rate are related to each other via the isospin rule, the lifetime of the ${}^3_\Lambda$H can be estimated via a hybrid method: theoretically computing the ${}^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$ decay rate and combining with the experimentally determined R_3 [11]. Thus, the ${}^3_\Lambda$H R_3 provides an additional handle to access its lifetime.

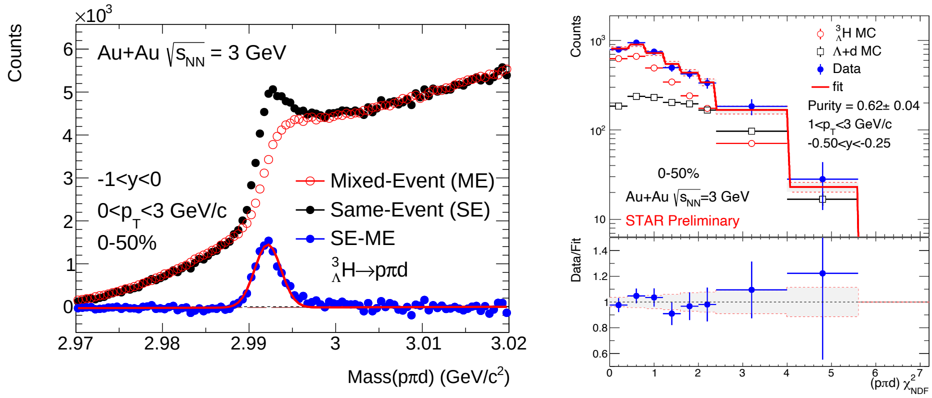

Figure 3. (left) Invariant mass of $d-p-\pi^-$ triplets from Au+Au collisions at $\sqrt{s_{NN}}$ =3.0 GeV. Data are shown as solid black markers, the combinatorial background estimated via event mixing is shown as the open red markers, and the background subtracted distribution is shown as the solid blue markers. (right, upper panel) Template fit to χ^2 of the secondary vertex fit. The solid blue markers represent the data after combinatorial background subtraction, red and black open markers represent contributions from signal and correlated background respectively. The solid red line indicates the sum of the components. (right, bottom panel) Ratio of the data after combinatorial background subtraction to the sum of the components.

The ${}^3_\Lambda$H yields are measured in $\sqrt{s_{NN}}$ = 3.0 GeV Au+Au collisions via both two-body and three-body decay channels. The extraction of ${}^3_\Lambda$H signal via its three-body decay is more complicated compared to the two-body decay due to significant contributions of correlated background in its invariant mass spectrum. As demonstrated in Fig. 3, after subtracting the combinatorial background which is estimated via event-mixing, a template fit is applied to the data to statistically separate contributions from correlated background and signal. The fit exploits the fact that, for true ${}^3_\Lambda$H signal, all three daughter tracks point to the same secondary vertex, which gives rise to smaller χ^2 values in the secondary vertex fit, while correlated background does not, and lead to larger χ^2 values.

By comparing the corrected yields from the two decay channels, R_3 can be determined. The preliminary result $R_3 = 0.27 \pm 0.03(stat) \pm 0.04(syst)$, as shown in Fig. 4, is consistent with previous measurements. Our new measurements provide improved precision to the ${}^3_\Lambda$H R_3, which, aside from its connection to the lifetime, may also provide constraints on its binding energy [11].

5 Summary and Outlook

In summary, recent studies on hypernuclei lifetimes and branching ratios from STAR have been discussed. New lifetime measurements of ${}^3_\Lambda$H, ${}^4_\Lambda$H, and ${}^4_\Lambda$He from the Beam Energy Scan II progam have been presented. In particular, the new ${}^3_\Lambda$H and ${}^4_\Lambda$H lifetime measurements are the most precise published results to date, providing strong constraints to hyperon-nucleon

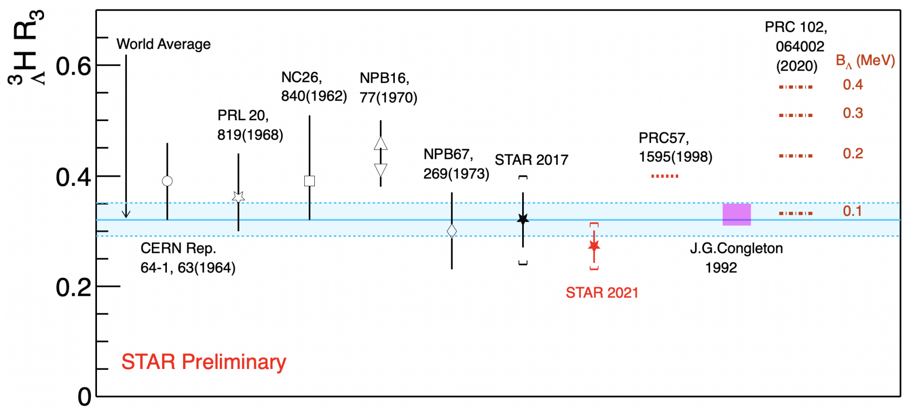

Figure 4. Compilation of ${}^{3}_{\Lambda}$H relative branching ratio R_3. The experimental average R_3 is indicated by the blue shaded band. The magenta box and dashed red and orange lines represent theoretical calculations.

interaction models. In addition, the ${}^{3}_{\Lambda}$H relative branching ratio R_3 has been extracted in $\sqrt{s_{NN}}$ = 3.0 GeV Au+Au collisions. The improved precision on R_3 provides the necessary input for connecting theoretically computed two-body mesonic decay rates and the ${}^{3}_{\Lambda}$H lifetime.

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