Study of Charge Symmetry Breaking in A = 4 hypernuclei in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at RHIC

Tianhao Shao[1] (for the STAR Collaboration)[*]

[1]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China

Abstract. In these proceedings, we present the measurement of the charge symmetry breaking in $A = 4$ hypernuclei in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. The signal reconstruction and binding energy measurements of ${}^4_\Lambda$H and ${}^4_\Lambda$He, including corrections on momentum, are discussed. Our result of Λ binding energy difference for ground states is $\Delta B_\Lambda(0^+) = 0.16 \pm 0.14(\text{stat.}) \pm 0.10(\text{syst.})$ MeV. Combined with the energy levels of excited states, the difference for excited states is $\Delta B_\Lambda(1^+) = -0.16 \pm 0.14(\text{stat.}) \pm 0.10(\text{syst.})$ MeV which shows a negative sign with a magnitude comparable to the result of ground states. These results are compared with previous measurements and theoretical model calculations.

1 Introduction

The charge symmetry of strong interactions predicts that the Λ-p and Λ-n interactions should be identical as they only differ in charge. This leads to the conclusion that the Λ binding energies of a pair of mirror hypernuclei should be identical. However, in 1970s nuclear emulsion experiments measured the Λ binding energy difference in $A = 4$ mirror hypernuclei, ${}^4_\Lambda$H and ${}^4_\Lambda$He, and found a difference of $\Delta B^4_\Lambda(0^+_{\text{g.s.}}) = 350 \pm 50$ keV [1]. Such a large difference cannot be explained by the mass difference between up and down quarks in nuclear systems. In 2015, the J-PARC E13 γ-ray spectroscopy experiment measured the transition energy from the 1^+ excited state to the ground state of ${}^4_\Lambda$He to be 1406±2±2 keV [2]. The E13 collaboration combined the Λ binding energies of ground states from emulsion experiments of 1970s [1] with a γ-ray transition energy for ${}^4_\Lambda$H measured in 1976 [3] and their new γ-ray transition energy measurement for ${}^4_\Lambda$He to determine the Λ binding energy difference in excited states to be $\Delta B^4_\Lambda(1^+_{\text{exc}}) = 30 \pm 50$ keV [2], which is much smaller than that in ground states. It was suggested that the charge symmetry breaking effect may have a large spin dependence. In 2016, the MAMI-A1 collaboration used spectrometers to provide a new measurement of the ground state Λ binding energy of ${}^4_\Lambda$H [4]. Combining their new measurement with the previous ${}^4_\Lambda$He Λ binding energy, and the measurements of the γ-ray transition energies for ${}^4_\Lambda$H [1] and ${}^4_\Lambda$He [2], they updated the estimate of the binding energy differences to be $\Delta B^4_\Lambda(0^+_{\text{g.s.}}) = 233 \pm 92$ keV and $\Delta B^4_\Lambda(1^+_{\text{exc}}) = -83 \pm 94$ keV. However many theoretical model calculations failed to reproduce the experimental results [5–9]. In 2016, the ab initio no-core shell model calculations plus a charge symmetry breaking $\Lambda - \Sigma^0$ mixing vertex of $A = 4$

[*]e-mail: shaoth21@outlook.com

hypernuclei obtained a large charge symmetry breaking in excited states and concluded that $\Delta B^4_\Lambda(1^+_{\rm exc}) \approx -\Delta B^4_\Lambda(0^+_{\rm g.s.}) < 0$ [10]. Independent measurements are crucially needed to test these calculations [11].

To study the physics of QCD matter in the high baryon density region, the STAR experiment ran fixed-target mode during the BES-II program. A stationary gold target was mounted inside the beam pipe. In the fixed-target mode, the lowest center-of-mass energy ($\sqrt{s_{\rm NN}}$) for Au+Au collisions that RHIC can effectively run is 3 GeV. In 2018, STAR took about 300 million events of Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 3 GeV fixed-target mode. Model calculations predict that the production yields of hypernuclei will reach the maximum value at about $\sqrt{s_{\rm NN}}$ = 5 GeV [12]. The STAR fixed-target program gives us an opportunity to study the Λ binding energy of ${}^4_\Lambda$H and ${}^4_\Lambda$He in the same experiment to address the charge symmetry breaking effect.

2 Analysis details and results

In this analysis, signals of ${}^4_\Lambda$H and ${}^4_\Lambda$He are analyzed in Au+Au collisions at 3 GeV. The ${}^4_\Lambda$H is reconstructed via its two-body decay channel ${}^4_\Lambda{\rm H} \to {}^4{\rm He} + \pi^-$ and the ${}^4_\Lambda$He is reconstructed via its three-body decay channel ${}^4_\Lambda{\rm He} \to {}^3{\rm He} + {\rm p} + \pi^-$. The decay daughters are identified based on the particles' energy loss $\langle dE/dx \rangle$ information from the Time Projection Chamber (TPC). The identification of ^{4}He and ^{3}He are carried out also with the mass information from the Time of Flight (TOF) detector. Then the invariant mass distributions of ${}^4_\Lambda$H and ${}^4_\Lambda$He are reconstructed according to their decay topologies using the KF Particle package [13]. To enhance the signal significance, the TMVA-BDT package [14] is used. Figure 1 shows the invariant mass distributions of ${}^4_\Lambda$H and ${}^4_\Lambda$He reconstructed in 0-100% centrality and (-2, 0) rapidity range. The centroids and statistical uncertainties for masses of the ground state

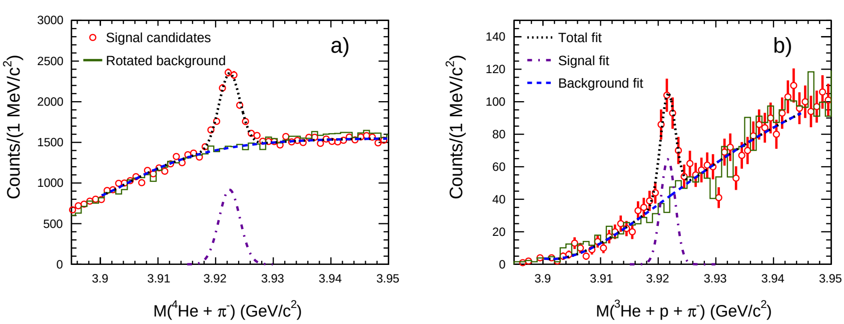

Figure 1. Invariant mass distributions for ${}^4_\Lambda$H and ${}^4_\Lambda$He reconstruction. The backgrounds are obtained by rotating ^{4}He or ^{3}He track by 180 degrees in the transverse plane. The black dashed curves represent fits with a Gaussian function plus double exponential functions. This figure is from [15].

${}^4_\Lambda$H and ${}^4_\Lambda$He are determined by fitting the invariant mass distributions with a gaussian plus double exponential function represented by black dashed curves in Fig. 1. The extracted masses are

$$m({}^4_\Lambda{\rm H}) = 3922.38 \pm 0.06({\rm stat.}) \pm 0.14({\rm syst.})\ {\rm MeV}/c^2,$$
$$m({}^4_\Lambda{\rm He}) = 3921.69 \pm 0.13({\rm stat.}) \pm 0.12({\rm syst.})\ {\rm MeV}/c^2.$$

Due to the particle's energy loss in material before entering the TPC and the finite precision in the measured magnetic field value at STAR, the reconstructed momenta of decay daughters need to be corrected. The first correction is for the particle's energy loss. This correction is done by using the STAR embedding data. The ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He samples from Monte Carlo pass through the GEANT simulation of the STAR detector geometry and material. Then the momentum loss of particles can be determined by comparing the momentum difference between MC input and detector output. The second correction is for the used magnetic field. From previous studies of the invariant masses of known particles, it has been determined that the used magnetic field value should be scaled by 0.2%, and therefore the momenta of particles are scaled with a factor 0.998 in this analysis. The Λ invariant mass measured in Au+Au collisions at 3 GeV with these two corrections is consistent with the PDG mass. Three sources of systematic uncertainties are included: magnetic field accuracy, energy loss correction, and BDT cut.

The Λ binding energies of hypernuclei can be calculated using the masses of a given hypernucleus and its constituents. The Λ binding energies for the ground states are:

$$\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{H}) = 2.22 \pm 0.06(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{MeV},$$
$$\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{He}) = 2.38 \pm 0.13(\mathrm{stat.}) \pm 0.12(\mathrm{syst.})\ \mathrm{MeV}.$$

The results for excited states can be obtained from the γ-ray transition energies [2, 3]. Then the Λ binding energy difference between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He can be calculated:

$$\Delta\mathrm{B}_{\Lambda}(0^{+}) = 0.16 \pm 0.14(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})\ \mathrm{MeV},$$
$$\Delta\mathrm{B}_{\Lambda}(1^{+}) = -0.16 \pm 0.14(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})\ \mathrm{MeV}.$$

In this analysis, the Λ binding energy difference for excited states is negative and its magnitude is comparable to the ground states within uncertainties. Our results are consistent with the theoretical prediction, $\Delta\mathrm{B}^{4}_{\Lambda}(1^{+}_{\mathrm{exc}}) \approx -\Delta\mathrm{B}^{4}_{\Lambda}(0^{+}_{\mathrm{g.s.}}) < 0$ [10], which is from the *ab initio* calculation using the hyperon-nucleon potential from the chiral effective field theory plus a charge symmetry breaking effect.

The results in this analysis are compared to previous measurements and theoretical model calculations in Fig. 2. Due to the low statistics of ${}^{4}_{\Lambda}$He, the statistical uncertainty on the ${}^{4}_{\Lambda}$He mass drives the statistical uncertainties on the Λ binding energy differences. STAR has taken about 2 billion events in fixed-target Au+Au collisions at 3 GeV in 2021. Detector upgrades are expected to increase the tracking and particle identification acceptance. The statistical uncertainties will be reduced and their expected magnitudes are shown as green shadows in Fig. 2.

3 Conclusions

To address the charge symmetry breaking effect in A = 4 hypernuclei, we reconstructed the invariant mass distributions of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He in Au+Au collisions at 3 GeV taken in fixed-target mode at STAR, from which the Λ binding energy difference between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He is determined. Using our results and the γ-ray transition energies from previous measurements, we show that the charge symmetry breaking effect in excited states has a negative value and its magnitude is comparable to that of the ground states within uncertianties. STAR has taken a factor of 7 more data for 3 GeV Au+Au collisions in 2021. The statistical uncertainties of this analysis will be reduced in the future work.

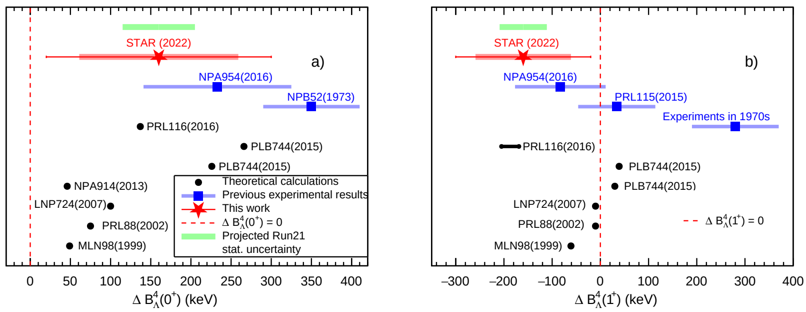

Figure 2. The Λ binding energy difference between ${}^4_\Lambda$H and ${}^4_\Lambda$He in ground states (left figure) and in excited states (right figure) compared with theoretical model calculations (black dots) [5–10] and previous measurements (blue squares) [1–4, 16]. Error bars show statistical uncertainties and shadows show the systematic uncertainties. The green shadows are projected statistical uncertainties for the 3 GeV data taken in 2021. This figure is from [15].

4 Acknowledegments

Finance support including the international travel expense in part by the National Natural Science Foundation of China under Contact No. 12025501 and the European Unions Horizon 2020 research and innovation programme under grant agreement No. 824093 are appreciated.

References

[1] M. Juric et al., Nucl. Phys. B **52**, 1 (1973)
[2] T.O. Yamamoto et al. (J-PARC E13), Phys. Rev. Lett. **115**, 222501 (2015), `1508.00376`
[3] M. Bedjidian, A. Filipkowski, J.Y. Grossiord, A. Guichard, M. Gusakow, S. Majewski, H. Piekarz, J. Piekarz, J.R. Pizzi (CERN-Lyon-Warsaw), Phys. Lett. B **62**, 467 (1976)
[4] F. Schulz et al. (A1), Nucl. Phys. **A954**, 149 (2016)
[5] A. Nogga, H. Kamada, W. Gloeckle, Phys. Rev. Lett. **88**, 172501 (2002), `nucl-th/0112060`
[6] J. Haidenbauer, U.G. Meissner, A. Nogga, H. Polinder, Lect. Notes Phys. **724**, 113 (2007), `nucl-th/0702015`
[7] A. Nogga, Nucl. Phys. A **914**, 140 (2013)
[8] S.A. Coon, H.K. Han, J. Carlson, B.F. Gibson, *Particle mixing and charge asymmetric Lambda N forces*, in *7th International Conference on Mesons and Light Nuclei 98* (1998), `nucl-th/9903034`
[9] A. Gal, Phys. Lett. **B744**, 352 (2015), `1503.01687`
[10] D. Gazda, A. Gal, Phys. Rev. Lett. **116**, 122501 (2016), `1512.01049`
[11] J. Chen, D. Keane, Y.G. Ma, A. Tang, Z. Xu, Phys. Rept. **760**, 1 (2018), `1808.09619`
[12] J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher, H. Stocker, Phys. Lett. B **714**, 85 (2012), `1203.2547`
[13] I. Kisel (CBM, STAR), J. Phys. Conf. Ser. **1602**, 012006 (2020)
[14] A. Hocker et al. (2007), `physics/0703039`
[15] M.S. Abdallah et al. (STAR) (2022), `2207.00778`
[16] M. Bedjidian et al. (CERN-Lyon-Warsaw), Phys. Lett. B **83**, 252 (1979)