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

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Abstract. In this paper, 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 measurement of $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He, including corrections and systematic uncertainty evaluation, are discussed. Combined with the energy levels of excited states, our preliminary result of Λ binding energy difference for excited states is $\Delta B_{\Lambda}(1^{+}) = -190 \pm 130(\text{stat.}) \pm 70(\text{syst.})$ keV which shows a negative value and its magnitude is comparable to the result of ground states $\Delta B_{\Lambda}(0^{+}) = 130 \pm 130(\text{stat.}) \pm 70(\text{syst.})$ keV. 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 cannot be influenced by charge. This leads to a conclusion that the Λ binding energies of a pair mirror hypernuclei should be identical. However, in 1970's nuclear emulsion experiments measured the Λ binding energies and the binding energy difference in A = 4 mirror hypernuclei, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He, and found a difference of $\Delta B^{4}_{\Lambda}(0^{+}_{g.s.}) = 350 \pm 50$ keV [1]. Such a large difference cannot be explained with the mass difference of the up and down quarks in nuclear systems. In 2015, the J-PARC E13 γ-ray spectroscopy experiment measured the transition energy from the 1^{+} first excited state of $^{4}_{\Lambda}$He to be $1406 \pm 2 \pm 2$ 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 measurement for $^{4}_{\Lambda}$He to determine the difference in excited states to be $\Delta B^{4}_{\Lambda}(1^{+}_{exc}) = 30 \pm 50$ 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 $\Delta B^{4}_{\Lambda}(0^{+}_{g.s.}) = 233 \pm 92$ keV and $\Delta B^{4}_{\Lambda}(1^{+}_{exc}) = -83 \pm 94$ 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 hypernuclei got a large charge symmetry breaking in excited states and concluded

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that $\Delta B_{\Lambda}^{4}(1_{exc}^{+}) \approx -\Delta B_{\Lambda}^{4}(0_{g.s.}^{+}) < 0$ [10]. Independent experiments are needed to test these calculations [11].

To study the physics of QCD matter in a high baryon density region, the STAR detector ran in fixed-target mode during the BES-II program. A stationary gold target was mounted inside the beam pipe and in two meters to the west of the center of the detector, which was in the plane of the west end-cap of the TPC detector. In collider mode, the lowest $\sqrt{s_{NN}}$ for Au+Au collisions that RHIC can effectively run is 7.7 GeV, whereas in fixed-target mode, this low energy limit can be extended down to 3 GeV. In 2018, STAR has taken about 300 million events data of Au+Au collisions at 3 GeV fixed target mode. Model calculations predict that the production yields of hypernuclei will become larger at lower collision energies [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 ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$. The ${}^{4}_{\Lambda}$He is reconstructed via its three-body decay channel ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$. The decay daughters are identified mainly according to the $\langle dE/dx \rangle$ information from the Time Projection Chamber (TPC). The identification of ^{4}He and ^{3}He are done also according to the mass information from the Time Of Flight (TOF) detectors. Then the invariant mass distributions of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are reconstructed according to their decay topology, similar to the analysis presented in Ref. [13]. To increase 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. The centroids and statistical uncertainties in the ground state masses of the ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are determined by fitting the invariant mass distributions with a Gaussian function plus double exponential functions represented by black dashed curves in Fig. 1. The mass results are

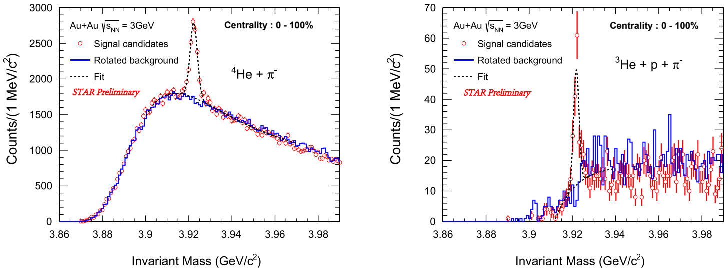

Figure 1. Invariant mass distributions for ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He reconstruction. The backgrounds are obtained by rotating ^{4}He or ^{3}He track by 180 degrees in the transverse plane. The black dashed curves represent fits with a Gaussian function plus double exponential functions.

$$\mathrm{m}({}^{4}_{\Lambda}\mathrm{H}) = 3922.36 \pm 0.06(\mathrm{stat.}) \pm 0.18(\mathrm{syst.})\ \mathrm{MeV/c^2}, \tag{1}$$

$$\mathrm{m}({}^{4}_{\Lambda}\mathrm{He}) = 3921.70 \pm 0.12(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{MeV/c^2}. \tag{2}$$

Due to the particle's energy loss in material prior the tracking region of the TPC and the precision of the magnetic field, the measured 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. Generated samples of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He from a Monte Carlo program are inputted into a GEANT virtual STAR detector. 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 magnetic field measurement accuracy. From previous studies of the invariant mass of known particles, it has been determined that the magnetic field of STAR detector should be scaled by 0.2%, therefore the momentum of particles are scaled with a factor 0.998 in this analysis. These two corrections have been checked in Λ invariant mass. The Λ invariant mass measured in Au+Au collisions at 3 GeV with these two corrections is consistent with the PDG mass. Four sources of systematic uncertainties have been analyzed: magnetic field accuracy, energy loss correction, BDT cut, and fit method.

The Λ binding energies of hypernuclei can be calculated using the mass of a given hypernucleus and its constituents:

$$\mathrm{B}_{\Lambda} = (\mathrm{M}_{\Lambda} + \mathrm{M}_{\mathrm{core}} - \mathrm{M}_{\mathrm{hypernucleus}})\mathrm{c}^2, \tag{3}$$

where $\mathrm{M}_{\mathrm{core}}$ represents the mass of a triton or ^{3}He taken from CODATA [15] for ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He respectively. The Λ binding energy results are:

$$\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{H}) = 2.24 \pm 0.06(\mathrm{stat.}) \pm 0.18(\mathrm{syst.})\ \mathrm{MeV}, \tag{4}$$

$$\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{He}) = 2.37 \pm 0.12(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{MeV}. \tag{5}$$

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

$$\Delta\mathrm{B}_{\Lambda}(0^{+}) = 130 \pm 130(\mathrm{stat.}) \pm 70(\mathrm{syst.})\ \mathrm{keV}, \tag{6}$$

$$\Delta\mathrm{B}_{\Lambda}(1^{+}) = -190 \pm 130(\mathrm{stat.}) \pm 70(\mathrm{syst.})\ \mathrm{keV}. \tag{7}$$

In this analysis, the difference in excited states shows a negative value and its magnitude is comparable to the ground states within uncertainties. Most of theroetical calculations predict small Λ binding energy differences in both ground states and excited states. Gazda and Gal reported a large splitting in ground states and also a large value in excited states with an opposite sign and a similar magnitude, $\Delta B^{4}_{\Lambda}(1^{+}_{exc}) \approx -\Delta B^{4}_{\Lambda}(0^{+}_{g.s.}) < 0$ [10], which is slightly favored by our preliminary results.

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 a factor of 7 more data (about 2 billion events) at 3 GeV fixed-target Au+Au collisions in run 2021. Upgrades to the TPC and the TOF have increased the tracking and PID acceptance. The statistical uncertainties will be reduced and their expected magnitudes are shown as green shadows shown 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. With the corrections for daughters' momenta the Λ binding energy difference between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He can be determined. Using our preliminary 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 at 3 GeV fixed-target in 2021. The statistical uncertainties of this analysis will be reduced in the future work.

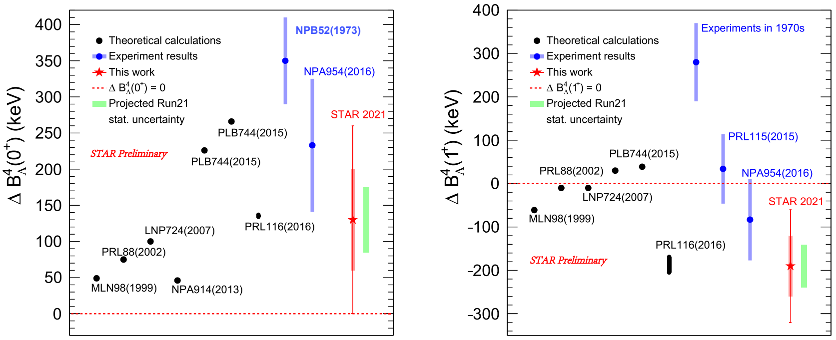

Figure 2. The Λ binding energy difference between ${}^4_\Lambda$H and ${}^4_\Lambda$He in ground states (left figure) and in excited states (right figure) compared with theoretical model calculations (black dots) [5–10] and previous measurements (blue dots) [1–4, 16]. Error bars show statistical uncertainties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

4 Acknowledegments

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