Observation of antimatter nuclei at RHIC-STAR

Yu-Gang Ma
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
E-mail: ygma@sinap.ac.cn

Abstract. In this article, we present a brief review on the recent measurements of antimatter particles at RHIC. We highlight the observations of the antihypertriton ($^3\bar{\Lambda}$H) and antihelium-4 nucleus ($^4\bar{\alpha}$, or $\bar{\alpha}$), and discuss the current experimental searches for antinuclei in cosmic rays. Finally we present a recent calculation result using thermal and coalescence mechanism for anti-light nuclei production.

1. Introduction

Relativistic heavy-ion collision create suitable conditions for a phase transition from hadron to deconfined quark matter which was predicted by the Lattice QCD calculation. During the collision, a hot and dense partonic matter can be formed, i.e. so-called Quark-Gluon Plasma (QGP). Many evidences have demonstrated that the QGP matter has been produced in central Au + Au collisions at RHIC energies [1, 2, 3, 4]. In the process, large amounts of energy are deposited into a more extended volume than that achieved in elementary particle collisions. These nuclear interactions briefly produce hot and dense matter containing roughly equal numbers of quarks and antiquarks. Then the QGP expands rapidly and cools down and undergoes a transition into a hadron gas, producing nucleons and their antiparticles. Therefore the relativistic heavy-ion collision can not only provide an environment to study strong interacting phase transition and QCD matter but also an ideal venue to produce antimatter particles.

The ideal of antimatter can be traced back to the end of 1890s, when Schuster discussed a hypothesis of the existence of antiatoms as well as antimatter solar system by hypothesis in his letter to Nature magazine [5]. However, the modern concept of antimatter is originated from the negative energy state solution of a quantum-mechanical equation, which was proposed by Dirac in 1928 [6]. Two years later, C. Y. Chao found that the absorption coefficient of hard $\gamma$-rays in heavy elements was much larger than that was expected from the Klein-Nishima formula or any other [7, 8]. This “abnormal” absorption is in fact due to the creation of the pair of electron and its anti-partner, so-called positron. This experiment gives the first indirect observation of the first anti-matter particle, namely positron. Two years later, Anderson observed positron with a cloud chamber [9]. Since the observation of the anti-proton ($\bar{p}$) [19] in 1955, antimatter nuclei such as $\bar{d}$, $^5\bar{\Pi}$, $^5\bar{\Xi}$ have been widely studied in both cosmic rays [10, 11, 12] and accelerator experiments [13, 14, 15, 16, 17, 18] for the purposes of dark matter exploration and the study of manmade matter such as quark gluon plasma, respectively.

The recent progress regard the observation of antihypertriton ($^3\bar{\Lambda}$) [20] and antihelium-4 ($^4\bar{\alpha}$, or $\bar{\alpha}$) [21] nucleus in relativistic heavy ion collisions reported by the RHIC-STAR
experiment as well as the longtime confinement of antihydrogen atoms [22] based on an antiproton decelarator facility by ALPHA collaboration have already created a lot of excitation in both nuclear and particle physics community. All of the measurements performed above have implications beyond the fields of their own. Such as, the study of hypernucleus in heavy ion collisions is essential for the understanding of the interaction between nucleon and hyperon (YN interaction), which plays an important role in the explanation of the structure of neutron star. Furthermore, as we learned from heavy ion collisions, the production rate for $^4\overline{\text{He}}$ produced by colliding the high energy cosmic rays with interstellar materials is too low to be observed. Even one $^4\overline{\text{He}}$ or heavier antinucleus that observed in the cosmic rays should be a great hint of the existence of massive antimatter in the Universe. Finally, the successful trap of antihydrogen atoms can lead to a precise test of the CPT symmetry law, as well as a measurement of the gravitational effects between antimatter and matter in the future.

In this article, we focus on the above mentioned discoveries on antihypertriton [20] and antihelium-4 [21] at the RHIC as well as the current effort of the hunting antimatter nuclei in cosmic rays. A brief review on the formation and observation of $^3\Lambda\overline{\text{H}}$ through their secondary vertex reconstructions via decay channel $^3\Lambda\overline{\text{H}} \rightarrow ^3\overline{\text{He}} + \pi^+$ with a branch ratio of 25% in high energy heavy ion collisions is presented in Sec. 2. Section 3 discusses the particle identification of $^3\overline{\text{He}}$ nucleus by measuring their mass value directly with the newly commissioned detector Time Of Flight (TOF) at RHIC-STAR. Section 4 discusses the status of the hunting antimatter nuclei in cosmic rays. In Section 5, we discuss the antimatter nuclei production mechanism. Finally we give a summary.

2. Observation of the first antimatter hypernucleus: $^3\Lambda\overline{\text{H}}$

Different from the normal (anti-)nuclei which only consist of (anti-) u and d quarks, (anti-)hypernucleus also includes the (anti-)strange quark degree of freedom, of which the typical one is $\Lambda$-hypernucleus. The simplest hypernucleus observed so far is hypertriton, which is composed of one neutron, one proton and one $\Lambda$-hyperon. Due to the presence of hyperon, hypernucleus provides an ideal environment to learn the hyperon-nucleon interaction, responsible in part for the binding of hypernuclei and lifetime, which is of fundamental interest in nuclear physics and nuclear astrophysics. So far, many hypernuclei have been identified, even for the observation of double-$\Lambda$ hypernucleus [23]. No anti-hypernucleus was observed until the STAR collaboration announced the first anti-matter hypernucleus, i.e. $^3\Lambda\overline{\text{H}}$ [20], in 2010. In the technique viewpoint, the identification of $^3\Lambda\overline{\text{H}}$ can be achieved by reconstructing their secondary vertex via the decay channel of $^3\Lambda\overline{\text{H}} \rightarrow ^3\overline{\text{He}} + \pi^+$, which occurs with a branching ratio of 25% (assuming that this branching fraction is the same as that for $^3\Lambda\text{H}$ [24]) [20, 25]. The data used for $^3\Lambda\overline{\text{H}}$ analysis was collected by the STAR experiment at Relativistic Heavy Ion Collider (RHIC), using the cylindrical Time Projection Chamber (TPC), which is 4 meters in diameter and 4.2 meters long in the beamline direction [26]. The identification of tracks can be achieved by correlating their ionization energy loss $\langle dE/dx \rangle$ in TPC with their magnetic rigidity. Figure 1C shows $\langle dE/dx \rangle$ for negative tracks versus the magnetic rigidity. The different bands stand for different kinds of particles. Figure 1D is the distribution of a new variable, $z = \text{Ln}(\langle dE/dx \rangle / (dE/dx)_B)$, which is used to identify $^3\overline{\text{He}}$ and $^3\Lambda\overline{\text{He}}$, here $\langle dE/dx \rangle_B$ is the expected value of $\langle dE/dx \rangle$.

Topological cuts including the distance between two daughter tracks $^3\overline{\text{He}}$ and $\pi^+$ (<1cm), distance of closest approach (DCA) between $^3\Lambda\overline{\text{H}}$ and primary vertex (<1cm), decay length of $^3\Lambda\overline{\text{H}}$(>2.4cm), and the DCA of $\pi$ track (>0.8cm), are employed to enhance the signal to background ratio. The invariant mass of $^3\Lambda\text{H}$ and $^3\Lambda\overline{\text{H}}$ were calculated based on the conservation of momentum and energy in the decay process. The results are shown in Figure 1A for $^3\Lambda\text{H}$ and Figure 1B for $^3\Lambda\overline{\text{H}}$. The successfully reproduced combinatorial background with a rotation strategy can be described by double exponential function: $f(x) \propto \exp[-(x/p_1)] - \exp[-(x/p_2)]$, where $\Lambda$ is the gravitational constant. The successfully reproduced combinatorial background with a rotation strategy can be described by double exponential function: $f(x) \propto \exp[-(x/p_1)] - \exp[-(x/p_2)]$, where $\Lambda$ is the gravitational constant.
where \( x = m - m(3He) - m(\pi) \), and \( p_1, p_2 \) are the parameters. Finally, the signals are counted by subtracting the double exponential background of \( ^3\Lambda H \) and \( ^3\bar{\Lambda}H \).

As an example to show how \( ^3\bar{\Lambda}H \) looks like, Figure 2 depicts a typical Au + Au collision reconstructed in the STAR TPC. Different tracks are curved by a uniform magnetic field of 0.5 T parallel to the beamline. The event of interest here includes a \( ^3\Lambda H \) candidate created at the primary collision vertex near the center of the TPC, where the dashed black line is the trajectory of the \( ^3\bar{\Lambda}H \) candidate, which cannot be directly measured. The heavy red and blue lines are the trajectories of the \( ^3He \) and \( ^3\pi + \) decay daughters, respectively, which are directly measured. The \( ^3\Lambda H \) travels a few centimeters before it decays.

The measurement of \( ^3\Lambda H \) (\( ^3\bar{\Lambda}H \)) lifetime provides us an effective tool to understand the Y(\( \Lambda \))-N(p,n) interactions [27, 24]. And, the secondary vertex reconstruction of \( ^3\Lambda H \) (\( ^3\bar{\Lambda}H \)) makes us to be able to perform a calculation of its lifetime, via equation \( N(t) = N(0)exp(-t/\tau) \), where \( t = l/(\beta\gamma c) \), \( \beta\gamma c = p/m \), \( l \) is the decay length of \( ^3\Lambda H \), \( p \) is their momentum, \( m \) is their mass value, while \( c \) is the speed of light. \( ^3\Lambda H \) and \( ^3\bar{\Lambda}H \) samples are combined together to get a better statistics, with the assumption of the same lifetime of \( ^3\Lambda H \) and \( ^3\bar{\Lambda}H \) base on the CPT symmetry.
Figure 2. A typical event in the STAR detector that includes the production and decay of $^3\Lambda\bar{\Pi}$ candidate: (A) with the beam axis normal to the page, (B) with the beam axis horizontal. See details in text. Adapted from the Ref. [20].

Figure 3. A) The yields of $^3\Lambda\bar{\Pi}$ (solid squares) and $\Lambda$ (open circles) vs $c\tau$ distribution. The solid lines stand for the $c\tau$ fits, and the insert plot describes $\chi^2$ distribution of the best fits. (B) Comparison between the present measurement and theoretical calculation [27, 24], as well as the previous measurements [28, 29, 30, 31, 32, 33]. Adapted from the Ref. [20].

Theory. The measured yield is corrected for the tracking efficiency and acceptance of TPC, as well as the reconstruction efficiency of $^3\Lambda\bar{\Pi}$ and $^3\Lambda\Pi$. Then, the $l/(\beta\gamma)$ distribution can be
fitted with an exponential function to extract the lifetime parameter $c\tau$. The best fitting with $\chi^2$ minimization method yielded $c\tau = 5.5^{+3.2}_{-1.4} \pm 0.08$, which corresponds a lifetime of $182^{+89}_{-54} \pm 27$ ps as shown in Figure 3A. Figure 3B shows a comparison of the present measurement with theoretical calculation [27, 24], as well as the previous measurements [28, 29, 30, 31, 32, 33]. It seems that the present measurement of $\Lambda^0$ lifetime is consistent with calculation with phenomenological $\Lambda^0$ wave function [27] and a more recent three-body calculation [24].

In hot and dense environment, high production rate of $\Lambda^0$ (3H) due to equilibration among strange quarks and light quarks (u,d) is proposed to be a signature of the formation of QGP [20, 34]. By comparing the yields of $\Lambda^0$ and $^3\text{He}$, the baryon strangeness correlation factor can be extracted. Our recent calculation [35] indicates that the strangeness population factor, $S_3 = \frac{^3\text{He}}{\Lambda^0}(\Lambda/p)$ of $\Lambda^0$ incorporates the $\Lambda/p$ ratio in order to remove the sensitivity on yield differences on $\Lambda$ and $p$ as a function of beam energy. It is interesting to note that $S_3$ increases with beam energy in a system with partonic interactions (Melting AMPT) while it is almost unchanged in a purely hadronic system (Default AMPT) from Fig. 4. The measurement from AGS [36], in spite of large statistical uncertainty, gives the value $1/3$. The AGS measurement of $S_3 = \frac{\Lambda^0}{^3\text{He}}(\Lambda/p)$ offers further indirect support for the lower value of $S_3$ at the AGS [36]. A preliminary $\frac{\Lambda^0}{^3\text{He}}$ result for Au+Au collisions at 200 GeV from the STAR Collaboration [37] allows us to infer that the measured $S_3$ at RHIC is consistent with unity within errors. These experimental results are consistent with the melting AMPT calculations and are in contrast to the default AMPT calculations. The data imply that the local correlation strength between baryon number and strangeness is sensitive to the effective number of degrees of freedom of the system created at RHIC, and this number is significantly larger in a system dominated by partonic interactions compared with a pure hadronic gas.

3. Observation of the heaviest antimatter nucleus: $^4\text{He}$

The STAR collaboration also reported its observation of $^4\text{He}$ nucleus [21, 41] in April 2011, with 10 billion gold-gold collisions taken in the year 2007 and 2010. In addition to the particle identification method by combining energy loss ($\langle dE/dx \rangle$) and rigidity provided by TPC, the observation of $^4\text{He}$ nucleus relies on the measured traveling time of tracks given by the barrel TOF [42] of the STAR experiment (Solenoidal Tracker At RHIC), which is composed of 120 trays, surrounding the Time Projection Chamber (TPC) [26]. TPC is the central detector used in our measurements of antimatter which is situated in a solenoidal magnetic field and is used for three-dimensional imaging of the ionization trail left along the path of charged particles as shown in Fig. 5. In this figure, tracks from an event which contains a $^4\text{He}$ are shown, with the $^4\text{He}$ track highlighted in bold red. The mass value of particles can be calculated via $m^2 = p^2(t^2/L^2 - 1)$ for particle identification, where $t$ and $L$ are the time of flight and path length of the track, respectively. On the other hand, the online high level trigger (HLT) was employed to select collisions which contain tracks with charge $Ze = \pm 2e$ for fast analysis. The trigger efficiency for $^4\text{He}$ is about 70% with respect to offline reconstruction, with a selection rate less than 0.4%. Fig. 6 presents the $\langle dE/dx \rangle$ versus rigidity ($p/|Z|$) distribution. The colored bands stand for the helium sample collected by HLT. A cut of the DCA less than 3 cm for negative tracks (0.5 cm for positive tracks) is used to reject the background. In the left panel, a couple of $^4\text{He}$ candidates are identified and well separated from $^3\text{He}$ at the low momentum region. A clear $^4\text{He}$ signal has been observed and centered around the expected $\langle dE/dx \rangle$ value of $^4\text{He}$ in the right panel.

The $\langle dE/dx \rangle$ of $^3\text{He}$ ($^4\text{He}$) and $^4\text{He}$ ($^4\text{He}$) merge together at higher momentum region, and $n_{dE/dx}$, defined as $n_{dE/dx} = \frac{1}{R} \ln(\langle dE/dx \rangle/\langle dE/dx \rangle^2)$ ($R$ is the resolution of $\langle dE/dx \rangle$), is used for further particle identification. Fig. 7 shows the combined particle identification with
Figure 4. The $S_3$ ratio as a function of beam energy in minimum-bias $\text{Au} + \text{Au}$ collisions from the default AMPT where the hadronic freedom of degree is dominated (open circles) and the melting AMPT where the partonic interaction is dominated (open squares) plus coalescence model calculations. The available data from AGS [36] are plotted for reference. The $\Lambda/p$ ratios from the model are also plotted. Adapted from the Ref. [35].

$n_{dE/dx}$ and $\text{mass}^2/Z^2$ value distribution. Two clusters of $^4\overline{\text{He}}$ and $^4\text{He}$ located at $n_{dE/dx} = 0$, $\text{mass}^2/Z^2 = 3.48 \ (\text{GeV}/c^2)^2$ can be clearly separated from $^3\overline{\text{He}}$ and $^3\text{He}$ as well as $^3\text{H}$ and $^3\overline{\text{H}}$ are presented in the top panel and bottom panel. By counting $^4\overline{\text{He}}$ signal with the cuts window $-2 < n_{dE/dx} < 3$ and $2.82 \ (\text{GeV}/c^2)^2 < \text{mass}^2/Z^2 < 4.08 \ (\text{GeV}/c^2)^2$ as indicated in the top panel, 16 $^4\overline{\text{He}}$ candidates are identified. Together with 2 $^4\text{He}$ candidates detected by TPC alone in the year 2007 which is presented in the figure, 18 $^4\overline{\text{He}}$ candidates are observed by the STAR experiment. So far, $^4\overline{\text{He}}$ is the heaviest antimatter nucleus observed in the world. Right after the public report of $^4\overline{\text{He}}$ from the STAR collaboration, the LHC-ALICE collaboration also claimed the observation of $4 \ ^4\overline{\text{He}}$ particles [43].
4. Experimental searches for antinuclei in Cosmic rays

As we discussed in previous sections, most efforts on searching for antinuclei center on in high-energy nuclear physics laboratories. Nevertheless, it is still a big challenge to capture any antinucleus in cosmos. The search of $^4\text{He}$ and heavier antinucleus in universe is one of the major motivations of space based apparatus such as the Alpha Magnetic Spectrometer [10]. Both the RHIC-STAR experimental result and model calculation provide a background estimation of $^4\text{He}$ for the future observation in Cosmos production [21]. Recently, the effort to search for the Cosmic-Ray Antideuterons and Antihelium by the Balloon-borne Experiment with Superconducting Spectrometer (BESS) collaboration has been made [44, 45]. However, no Antideuterons candidate was found using data collected during four BESS balloon flights from 1997 to 2000 [44]. No Antihelium candidate was found using data collected during four BESS balloon flights from 1997 to 2000 [44]. They derived an upper limit of $1.9 \times 10^{-4} (m^2 s sr GeV/nucleon)^{-1}$ for the differential flux of cosmic-ray antideuterons, at the 95% confidence level, between 0.17 and 1.15 GeV/nucleon at the top of the atmosphere [44].

Figure 5. A three-dimensional rendering of the STAR TPC surrounded by the TOF barrel shown as the outermost cylinder. Tracks from an event which contains a $^4\text{He}$ are shown, with the $^4\text{He}$ track highlighted in bold red. Adapted from the Ref. [21].
antihelium, assuming that antihelium has the same spectral shape as helium, a 95% confidence upper limit for the possible abundance of antihelium relative to helium of $6.9 \times 10^{-8}$ was determined combining all BESS data, including the two BESS-Polar flights. With no assumed antihelium spectrum and a weighted average of the lowest antihelium efficiencies for each flight, an upper limit of $1.0 \times 10^{-7}$ from 1.6 to 14 GV was determined for the combined BESS-Polar data. Under both antihelium spectral assumptions, these are the lowest limits obtained to date [44]. Fig. 12 shows the new upper limits of antihelium/helium from the BESS experiment [44]. The search for antihelium in cosmos remains an experimental challenge.

5. Production mechanisms of antimatter light-nucleus

Antimatter particles including $\pi, p, \bar{p}, ^3\bar{H}, ^3\bar{H}, ^4\bar{H}, ^3\bar{He}$ and antihydrogen atoms have been observed in the past eighty years. Most of these antimatter particles were produced by nucleon-nucleon reactions, where their production rate can be described by both thermodynamic model and coalescence model [46, 47, 48, 49]. In thermodynamic model, the system created is characterized by the chemical freeze-out temperature ($T_{ch}$), kinetic freeze-out temperature ($T_{kin}$), as well as the baryon and strangeness chemical potential $\mu_B$ and $\mu_S$, respectively. (Anti)nucleus is regarded as an object with energy $E_A = Am_p$ (A is the atomic mass number, $m_p$ is the mass of proton) emitted by the fireball [46]. The production rate are proportional to the Boltzmann factor $e^{-m_p A/T}$ as shown in Equ. (1),

$$E_A \frac{d^3N_A}{d^3P_A} = \frac{gV}{(2\pi)^3} E_A e^{-m_p A/T},$$

where $P_A$ and $g$ are the momentum and degeneracy of (anti)nucleus, $V$ is the volume of the fireball. In coalescence picture, (anti)nucleus is formed by coalescence at the last stage of the system evolution since there exists strong correlation between the constituent nucleons in their
Figure 7. Top (bottom) panel shows the $n_{\sigma dE/dx}$ versus $mass^2/Z^2$ distribution for negative (positive) particles. The horizontal dashed lines mark the $n_{\sigma dE/dx} = 0$, while the vertical ones stand for the theoretical mass values of $^3\text{He}(^3\text{He})$ and $^4\text{He}(^4\text{He})$. The signals of $^4\text{He}$ and $^4\text{He}$ are counted in the cuts window of $-2 < n_{\sigma dE/dx} < 3$ and $2.82(\text{GeV}/c^2)^2 < mass^2/Z^2 < 4.08(\text{GeV}/c^2)^2$. Adapted from the Ref. [41].

phase space [18, 50, 51]. The production probability is described by Equ. (2),

$$E_A \frac{d^3 N_A}{d^3 P_A} = B_A (E_p \frac{d^3 N_p}{d^3 P_p})^2 (E_n \frac{d^3 N_n}{d^3 P_n})^{A-Z}. \quad (2)$$
The new upper limits of antihelium/helium at the top of the atmosphere calculated assuming the same energy spectrum for He as for He with previous experimental results. The limit calculated with no spectral assumption is about 25% higher. Adapted from Ref. [45].

\[ E_{dN/dp} \] stands for the invariant yield of nucleons or (anti)nucleus, \( Z \) is the atomic number. And, \( p_A, p_p, p_n \) are the momentum of (anti)nucleus, protons and neutrons, with \( p_A = A \times p_p \) is assumed. \( B_A \) is the coalescence parameter.

Figure 9 shows the calculated differential yields of \( p(\bar{p}), \Lambda(\bar{\Lambda}) \), and light (anti)nuclei as well
Figure 9. Differential invariant yields versus \( p_T \) distributions for \( p(\bar{p}) \), \( \Lambda(\bar{\Lambda}) \), and light (anti)nuclei, as well as (anti)hypertriton and di-\( \Lambda \). The open symbols are experimental data points from the STAR measurement \([52, 53, 18]\), and the black lines represent our calculations from the hydrodynamical blast-wave model plus a coalescence model. Adapted from Ref. \([49]\).

as (anti)hypertriton versus transverse momentum (\( p_T \)) distribution. Our calculations \([49]\) based on the hydrodynamic motivated BlastWave model can reproduce the data points extracted by the STAR experiment \([52, 53, 18]\). Within the same framework, we make predictions for the production rates of \( \Lambda(\bar{\Lambda}) \) and \( ^4\text{He} \) \((\bar{^4}\text{He})\) etc by coupling with a naive coalescence model \([49]\). With those production rates, we can explore relative particle production abundance of (anti)nucleus and compare with data taken at RHIC. Figure 10 shows the particle ratios of (anti)nucleus, both thermal model \([46]\) and coalescence model \([49]\) can fit the antinucleus to nucleus ratios at RHIC energy. While the coalescence model has a better description for \( ^3\Lambda^\text{H}/^3\text{He} \) and \( ^3\bar{\Lambda}^\text{H}/^3\bar{\text{He}} \) than thermal model \([49]\). In a microscopic picture, both coalescence and thermal production of (anti)nucleus predict an exponential trend for the production rate as a function of baryon number. The exponential behavior of (anti)nucleus production rate in nuclear nuclear reaction has been manifested in Figure 11, which depicts the invariant yields \( (d^2N/(2\pi p_T dp_T dy)) \) evaluated at the average transverse momentum \((p_T/|B| = 0.875 GeV/c)\) region versus baryon number distribution. The solid symbols represent our coalescence model calculation, which can fit the measured data points very well. By fitting the model calculation with an exponential function \( e^{-r|B|} \), a reduction rate of \( 1692 (1285) \) can be obtained for each additional antinucleon (nucleon) added to antinucleus (nucleus), compared to \( 1.6^{+0.6}_{-0.2} \times 10^3 \) \((1.1^{+0.3}_{-0.2} \times 10^3)\) for nucleus and (antinucleus) obtained by the STAR experiment. The yield of next stable antinucleus (antilithium-6) is predicted to be reduce by a factor of \( 2.6 \times 10^6 \),
Figure 10. The comparison of particle ratios between data and model calculations. The data points are taken from the STAR and the PHENIX experiments [20, 21, 17, 3]. The coalescent results are based on naive coalescence algorithm with a momentum difference lower than 100 MeV and a coordinate space difference less than 2R (R is the nuclear force radius), while the thermal predication is taken from [46]. Adapted from Ref. [49].

compare to \(^4\overline{He}\), and is impossible to be produced within current accelerator technology. The excitation of (anti)nucleus from a highly correlated vacuum was discussed in reference [54]. This new production mechanism can be tested with the measurement of the production rate of (anti)nucleus, any deviation of the production rate of (anti)nucleus from usual reduction rate, may indicate the exist of the direct excitation mechanism. The low production rate of \(^4\overline{He}\) antinucleus in nuclear interaction implies that any observation of of \(^4\overline{He}\) or even heavier antinucleus should be indicative of the existence of a large amount of antimatter somewhere in the Universe.

6. Summary

We present a brief review on the \(^4\overline{He}\) which is the heaviest antimatter nucleus observed so far [21] as well as \(^3\overline{H}\) which is the first antimatter hypernucleus [20]. Observation of both anti-nuclei demonstrates that the RHIC is an excellent facility for antimatter production. In the viewpoint of antimatter production, thermal model and coalescence model can essentially describe the production yield of antimatter and antimatter-matter ratio. In our recent calculation based on the hydrodynamic motivated BlastWave model coupled with a coalescence model at RHIC energy, we demonstrate that the current approach can reproduce the differential invariant yields and relative production abundances of light antinuclei and antihypernuclei [49]. The exponential
Figure 11. Invariant yields $d^2N/(2\pi p_T dp_T dy)$ of (anti)nucleus at the average transverse momentum region ($p_T/|B| = 0.875 GeV/c$) as a function of baryon number ($B$). The open symbols represents the data points extracted by the STAR experiment at RHIC energy, while solid ones are reproduced by coalescence model. The lines represent the exponential fit for our coalescence results of positive particles (right) and negative particles (left) with formula $e^{-r|B|}$. Adapted from Ref. [49].

behavior of the differential invariant yields versus baryon number distribution is studied. By extrapolating the distribution to $B = -6$ region, the production rate of $^6\text{Li}$ in high energy heavy ion collisions is about $10^{-16}$, its observation with the current accelerator technology seems impractical. As addressed in Sec. 4, the observation of $^4\text{He}$ and even heavier antinuclei in Cosmic rays is a great hint of the existence of massive antimatter in Universe. Model calculations and experimental measurements in high energy heavy ion collisions can simulate the interactions between high energy protons and interstellar materials. Thus current STAR results and model calculations provide a good background estimation for the future observation of $^4\text{He}$ and even heavier antinuclei in Universe.

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