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Hypertriton production in relativistic heavy ion collisions

Zhen Zhang *, Che Ming Ko

Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA

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ABSTRACT

Based on the phase-space distributions of freeze-out nucleons and Λ hyperons from a blast-wave model, we study hypertriton production in the coalescence model. Including both the coalescence of Λ with proton and neutron as well as with deuteron, which is itself formed from the coalescence of proton and neutron, we study how the production of hypertriton is affected if nucleons and deuterons are allowed to stream freely after freeze-out. Using central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ as an example, we find that this only reduces slightly the hypertriton yield, which has a value consistent with the experimental data, even if the volume of the system has expanded to a size similar to the freeze-out volume for a hypertriton if its dissociation cross section by pions in the system is given by its geometric size. Our results thus suggest that the hypertriton yield in relativistic heavy ion collisions is essentially determined at the time when nucleons and deuterons freeze out, although it still undergoes reactions with pions.

1. Introduction

Besides allowing the opportunity to study the properties of strongly interacting matter at extreme temperature and density, high energy heavy-ion collisions also provide the possibility to produce hypernuclei that contain strange baryons [1–3]. Because of the abundant anti-strange quarks produced in ultrarelativistic heavy ion collisions, anti-hypernuclei can also be produced in these collisions. Indeed, both hypertriton, which is a bound state of proton, neutron and Λ hyperon, and its anti-nucleus, i.e., the anti-hypertriton, have been detected at the Relativistic Heavy Ion Collider (RHIC) by the STAR Collaboration [4] and at the Large Hadron Collider (LHC) by the ALICE Collaboration [5] through their weak decays ${}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-$ and ${}^3_\Lambda\bar{\mathrm{H}} \to {}^3\bar{\mathrm{He}} + \pi^+$, respectively, with the same branch ratio of about 25% [6]. The study of hypernuclei production in high-energy heavy-ion collisions is also of interest because it can provide information on local baryon and strangeness correlations in the collisions [7], if their production is through the coalescence of protons, neutrons and Λ hyperons at the final stage of the collisions [8]. For example, the ratio $S_3 = {}^3_\Lambda\mathrm{H}/({}^3\mathrm{He} \times \frac{\Lambda}{p})$ [9] has been suggested as a possible probe of the onset of deconfinement in high-energy heavy-ion collisions [10].

In addition to the coalescence model mentioned in the above, hypernuclei production in relativistic heavy ion collisions has also been studied using the statistical model [3], in which their abundances are determined by assuming that they are in chemical equilibrium with other hadrons and nuclei at a chemical freeze-out temperature that is close to that for the quark–gluon plasma to hadronic matter phase transition. This is in stark contrast to the coalescence model, which assumes that hypernuclei are formed from the coalescence of protons, neutrons and Λ hyperons at the kinetic freeze-out of heavy ion collisions [8,11]. Both models are, however, quite successful in describing the experimental data, although slightly earlier freeze out of Λ hyperons than nucleons is introduced in the coalescence model study of Ref. [11]. The reason for this may be due to the fact that their numbers remain unchanged during the hadronic evolution from the chemical to the kinetic freeze out, like the deuteron [12] and other particles, which has recently been shown to be associated with the conservation of entropy per particle [13].

Given its very small binding energy of about 130 keV [14] and large root-mean-square radius of about 4.9 fm [15], the hypertriton is, however, expected to be formed later than the kinetic freeze out time for nucleons and Λ hyperons due to its larger dissociation cross section by pions and thus shorter mean-free path than these hadrons. To illustrate the effect of the large hypertriton size on its production in relativistic heavy ion collisions, we use the coalescence model based on the phase-space distributions of freeze-out nucleons and Λ hyperons from a blast-wave model. In particularly, we use the blast-wave models FOAu-N and FOAu-Λ of Refs. [11,16] for central (0%–10% centrality) Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [5]. Besides the coalescence of proton, neutron and Λ hyperon,

* Corresponding author.
E-mail addresses: zhenzhang@comp.tamu.edu (Z. Zhang), ko@comp.tamu.edu (C.M. Ko).

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we also include the coalescence process $d + \Lambda \to {}^3_\Lambda\text{H}$ between the deuteron d and Λ, which is found to enhance the hypertriton yield by about a factor of two, to take account of the fact that the hypertriton wave function is dominated by a Λ hyperon that is loosely bonded to a deuteron [5,15,17]. We find that the yield of hypertriton obtained from the coalescence model does not change much if it is calculated with nucleons and Λ that are allowed to stream freely after freeze out to a volume that is nineteen times larger, similar to the hypertriton freeze-out volume that is obtained with a dissociation cross section given by its geometrical size.

This paper is organized as follows. In Secs. 2 and 3, we briefly introduce the blast-wave fireball model and the coalescence model, respectively. Our results and related discussions on the hypertriton yield in central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented in Sec. 4. Finally, we give the conclusion in Sec. 5.

2. The blast wave model

Following Refs. [11,16], we use a blast-wave model to describe the phase-space distributions of nucleons and Λ hyperons at the kinetic freeze out of a heavy ion collision. With the assumption that the longitudinal proper time $\tau = \sqrt{t^2 - z^2}$ for the freeze-out hypersurface Σ^μ has a Gaussian distribution,

$$J(\tau) = \frac{1}{\sqrt{2\pi}\,\Delta\tau}\exp\left[-\frac{(\tau-\tau_0)^2}{2(\Delta\tau)^2}\right], \tag{1}$$

with a mean value τ_0 and a dispersion $\Delta\tau$, the single-particle invariant momentum spectrum of nucleons or Λ is then given by

$$E\frac{d^3N}{d^3p} = \int d\tau\, J(\tau) \int_{\Sigma^\mu} d^3\sigma_\mu p^\mu f(x,p), \tag{2}$$

where σ_μ is the covariant normal vector to Σ_μ and p^μ is the four-momentum of the emitted particle. The invariant distribution of these emitted particles from the hyper-surface is

$$f(x,p) = \frac{g}{(2\pi)^3}\left[\exp(-p^\mu u_\mu/T)/\xi \pm 1\right]^{-1}, \tag{3}$$

where g is the spin degeneracy factor of the particle, u_μ is the flow four-velocity, ξ is the fugacity parameter determined by the number of emitted particles, and T is the temperature of the fireball. Taking the longitudinal flow velocity to be $v_L = z/t$, the longitudinal flow rapidity is then $\eta_{\rm flow} = \frac{1}{2}\ln[(1+v_L)/(1-v_L)]$ and is identical to the space–time rapidity $\eta = \frac{1}{2}\ln[(t+z)/(t-z)]$. In terms of η, the transverse flow rapidity $\rho = \frac{1}{2}\ln[(1+\beta)/(1-\beta)]$ with β being the magnitude of the transverse flow velocity, one then has

$$p^\mu u_\mu = m_T\cosh\rho\cosh(\eta - y) - p_T\sinh\rho\cos(\phi_p - \phi_b), \tag{4}$$

$$p^\mu d^3\sigma_\mu = \tau m_T\cosh(\eta - y)d\eta r dr d\phi. \tag{5}$$

In the above, p_T and $m_T = \sqrt{m^2 + p_T^2}$ are the transverse momentum and mass with m being the particle mass, ϕ_p and ϕ_b are the azimuthal angles of the particle transverse momentum and the transverse flow velocity with respect to the reaction plane, and r and ϕ are the radial and angular coordinates of the particle in the transverse plane. For central heavy-ion collisions considered in the present study, the azimuthal angle of the transverse flow velocity ϕ_b is equal to ϕ and the transverse flow rapidity of the fluid element in the fireball can be parametrized $\rho = \rho_0 r/R_0$, with ρ_0 being the maximum transverse flow rapidity and R_0 the transverse radius of the fireball. The phase-space distributions of freeze-out particles are thus determined by the parameters T, ρ_0, R_0, τ_0, $\Delta\tau$, ξ_p, ξ_n, and ξ_Λ in the blast-wave model.

We note that by assuming freeze-out at constant longitudinal proper, we have neglected the effect that the edge of the fireball freezes out much earlier than the center. Although this effect can be included by free-streaming the frozen-out particles from the realistic decoupling surface to one of constant longitudinal proper time, which is expected to render these particles no longer perfectly thermal, it is not expected to significantly change our results as the parameters used in the present study are tuned to reproduce the experimental data on the transverse momentum spectra of nucleons and Λ hyperons.

3. The coalescence model

In the coalescence model, the production probability of a cluster is determined by the overlap of the Wigner function of its internal wave function with the phase-space distributions of the constituent particles at the kinetic freeze-out of heavy ion collisions. The multiplicity of a cluster containing M particles can then be written as [16,18–23]

$$N_M = g_M \int \left[\prod_{i=1}^{M} d\tau_i J(\tau_i) p_i^\mu d^3\sigma_{i\mu}\frac{d^3p_i}{E_i} f(x_i,p_i)\right] \times f_M(\boldsymbol{x}'_1,\cdots,\boldsymbol{x}'_M;\boldsymbol{p}'_1,\cdots,\boldsymbol{p}'_M) \tag{6}$$

where $f_M(\boldsymbol{x}'_1,\cdots,\boldsymbol{x}'_M;\boldsymbol{p}'_1,\cdots,\boldsymbol{p}'_M)$ is the Wigner function of the cluster and $g_M = (2S+1)/\left[\prod_{i=1}^M(2S_i+1)\right]$ is the statistical factor with S_i and S being the spins of the ith constituent particle and the cluster, respectively. The coordinate x_i and momentum p_i are those of the ith particle in the fireball frame, while x'_i and p'_i are the corresponding ones after Lorentz transforming to the rest frame of the produced cluster and then propagating earlier freeze-out particles freely to the time when the last particle in the cluster freezes out [20,22].

The Wigner function of a cluster is obtained from the Wigner transform of its internal wave function, which is usually taken to be the product of harmonic oscillator wave functions [16,20–23]. For example, using the ground-state wave function of a harmonic oscillator for the deuteron, its Wigner function is given by

$$f_d(\boldsymbol{\rho},\boldsymbol{p}_\rho) = 8\exp\left[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \boldsymbol{p}_\rho^2\sigma_\rho^2\right], \tag{7}$$

where the relative coordinate $\boldsymbol{\rho}$ and momentum $\boldsymbol{p}_\rho$ between the proton and neutron are defined, respectively, by

$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\boldsymbol{x}'_p - \boldsymbol{x}'_n), \tag{8}$$

$$\boldsymbol{p}_\rho = \sqrt{2}\frac{m_n\boldsymbol{p}'_p - m_p\boldsymbol{p}'_n}{m_p + m_n}, \tag{9}$$

with m_p and m_n being the masses of proton and neutron, respectively. The width parameter σ_ρ in Eq. (7) is related to the root-mean-squared charge radius of deuteron by

$$\langle r_d^2\rangle = \frac{3m_p^2}{(m_n+m_p)^2}\sigma_\rho^2. \tag{10}$$

Using the deuteron charge radius $\sqrt{\langle r_d^2\rangle} = 2.142$ fm [24] and $m_p = m_n = 0.939$ GeV, we find the width parameter to have the value $\sigma_\rho = 2.473$ fm. In the present study, we will use the Wigner function given by Eq. (7) in the coalescence model to study deuteron production.