Anti-$d$ and Anti-$He$ Production in $Au+Au$ Collisions at RHIC

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Ultra-relativistic $Au+Au$ collisions at RHIC ($\sqrt{s}=130, 200$ GeV) are used to study production of rare anti-nuclei. These clusters of anti-nucleons are formed by coalescence, i.e. overlapping wave functions of anti-nucleons. The coalescence coefficients $B_2$ for Anti-$d$ and $B_3$ for Anti-$^3He$ are determined, and used to derive the fireball radius.

1. Introduction

The STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, New York, USA, investigates novel QCD phenomena at high density and high temperature in ultra-relativistic $Au+Au$ collisions. RHIC has a diameter of 3.8 km, and in total 1740 superconducting magnets [1]. The highest center-of-mass energy ($\sqrt{s}=200$ GeV) is about a factor 10 higher than past fixed target experiments (e.g. CERN SPS $E_{beam}=160$ GeV, equivalent to $\sqrt{s}=18$ GeV). The main STAR subdetector is a midrapidity ($|\eta|\leq 1.6$) Time Projection Chamber (TPC, $R=2$ m, $L=4$ m) [2] with $\simeq 48,000,000$ pixels. In 3 years of data taking, high statistics ($10^6 \leq N \leq 10^7$ events on tape) for $Au+Au$, $p+p$ and $d+Au$ at $\sqrt{s}=200$ GeV and $Au+Au$ at $\sqrt{s}=130$ GeV were recorded, which enabled analyses of rare events.

The particle identification of anti-particles is performed by energy loss $dE/dx$, corresponding to charged particle ionization in the TPC gas (10% methane, 90% argon). As production of Anti-$He$ is a rare process ($dN/dy\sim 10^{-6}$), a level-3 trigger system [3] was used for realtime anti-nuclei identification. One central $Au+Au$ collision contains about $\simeq 130,000$ TPC hits and $\simeq 6,500$ TPC tracks, which were fully reconstructed in realtime ($t\leq 100$ ms) by 432 Intel i960 CPUs and 48 ALPHA 21264 CPUs, respectively. The trigger signature was a tag onto a negative charge $Q=-2$, by usage of the TPC $dE/dx$ in realtime. As no other particles in nature are expected to have the same signature, the signature is clean. For a single track, $\leq 45$ $dE/dx$ samples (corresponding to 45 TPC hits) were used for the calculation of a 70% truncated mean (i.e. excluding samples in the Landau tail of the $dE/dx$ distribution). A track quality cut of $N_{Hist}\geq 23$ hits per track on the level-3 trigger and $N_{Hist}\geq 30$ in the offline analysis was applied. Anti-$He$ candidate tracks were also required to have a distance-of-closest-approach to the event collision

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vertex of $\leq 7.5$ cm (trigger) and $\leq 3.0$ cm (offline). The TPC $dE/dx$ resolution was 11% (trigger) and 8% (offline). The particle identification cuts were $0.7 < dE/dx/I_{BB}$ (trigger) and $0.88 < dE/dx/I_{BB} < 1.28$ (offline), where $I_{BB}$ denotes the expected Bethe-Bloch ionization. For a particle or anti-particle of $p_T=1$ GeV/c, the level-3 trigger $p_T$ resolution is $\simeq 2\%$ (at an solenoidal magnetic field of $B=0.5$ T) and the track finder efficiency $\varepsilon \simeq 75\%$.

At the beginning of high luminosity RHIC spills, an level-3 trigger Anti-$He$ candidate enhancement factor of $\sim 4.2$ was achieved.

2. Anti-Nuclei

As nuclei are completely made of matter, there is trivially no anti-matter in the initial state. The dominant anti-nuclei production mechanism is 2-step, namely (1) pair production of $p\bar{p}$, $n\bar{n}$, followed by (2) coalescence, i.e. the anti-nucleon wave functions overlap inside a homogeneity volume. For the systematic study of the $A$ dependence of production yields, it is useful to define an invariant yield

$$E \frac{d^3N_A}{d^3P} = B_A(E \frac{d^3N_N}{d^3P})^A \quad (1)$$

with $p=P/A$.

The coalescence coefficient $B_A$ denotes the probability, that $A$ anti-nucleons form a bound state. It might be regarded as a “penalty factor” for the step from $n$ to $n+1$ anti-nucleons in the system. Typical orders of magnitude are $B_2 \sim 10^{-3}$ and $B_3 \sim 10^{-6}$. For high $\sqrt{s}$ and a large system size, the coalescence coefficient is related to the inverse of the effective volume containing the anti-nuclei (i.e. the fireball volume) by $B_A = 1/V_{eff}^{A-1}$. Thus, the coalescence coefficient can be used to determine the size of the system (Ch. 6), and compared with sizes from other, complementary methods such as $\pi^+\pi^\pm$ interferometry [4].

An additional motivation for the investigation of Anti-$He$ production in the laboratory is the possibility of comparison to Anti-$He$ production in the universe. Recently, a search for Anti-$He$ in the earth orbit was performed by the space shuttle-bound experiment AMS [5]. Two possible production mechanisms are known. On the one hand, as $\sim 24\%$ of all $He$ in the universe is primordial and was formed at $t \simeq 1$ s. Thus, an interesting question is, if primordial Anti-$He$ exists, too. On the other hand, $pA$, $\mu A$, $AA$ collisions$^2$ in the stellar medium permanently create anti-nuclei. Measurements of the coalescence parameters $B_A$ at high $\sqrt{s}$ are needed for estimates of abundances for both production mechanisms [6]. Results for Anti-$d$ and Anti-$He$ production at $\sqrt{s}=130$ GeV are published in [7]. Preliminary results for $\sqrt{s}=200$ GeV are reported in [8]. This paper reports the final results at $\sqrt{s}=200$ GeV based upon a factor 2 increased statistics [9], using a final data set of:

- at $\sqrt{s}=130$ GeV (year 2000), $6.3 \times 10^6$ $Au+Au$ collisions without trigger (solenoidal field $B=0.25$ T, 18% most central events), and

$^2$Heavy nuclei in the stellar medium are mainly produced in supernova explosions.
3. Anti-$d$ Yield

Anti-$d$ could only be identified cleanly in a small range $0.4 \leq p_T \leq 1.0$ GeV/$c$, as $dE/dx$ bands merge for $p_T \geq 1.0$ GeV/$c$. An additional rapidity cut if $|y| \leq 0.3$ was required in order to filter long tracks. The uncorrected raw yield is $N_{\text{Anti}-d}=6416$. Invariant yields are listed in Tab. 3 in comparison with published yields at $\sqrt{s}=130$ GeV [7]. An absorption correction, based upon a parametrized annihilation cross section, is applied [9].

4. Anti-$^3He$ Yield.

For Anti-$^3He$, a clean $dE/dx$ identification is possible over the wide range $1.0 \leq p_T \leq 5.0$ GeV/$c$. Thus, a wider rapidity cut $|y| \leq 1.0$ could be applied without compromising the signal significance. The final raw yield is $N_{\text{Anti}-^3He}=193$ and shown in Fig. 2 and Fig. 3. Invariant yields are listed in Tab. 3 in comparison with published yields at $\sqrt{s}=130$ GeV [7].

5. Coalescence Parameters $B_2$, $B_3$

Using a measured invariant yield for anti-protons $E \frac{d^2N}{dp} = 0.7-2.5$ GeV$^{-2}$c$^3$ [7] as additional input, the coalescence parameters $B_2$ for Anti-$d$ (Fig. 4) and $B_3$ for Anti-$^3He$ (Fig. 5) could be determined from the yields. In can be seen, that RHIC represents the
highest $\sqrt{s}$, a factor 10 higher than past experiments. Both $B_2$ and $B_3$ decrease as a function of $\sqrt{s}$. According to $B_A \sim 1/V_A^{-1}$ (Ch. 2), this can be interpreted by increasing fireball volume.

### 6. Volume of Homogeneity

In a model, which combines coalescence, hydrodynamics and source expansion [10], the $A$ dependence of the coalescence mechanism can be calculated. Thus, a homogenity volume $V_{hom}$ can be defined, which does not depend on $A$ anymore.

$$V_{eff}(A, M_T) = \left( \frac{2\pi}{A} \right)^{3/2} V_{hom}(m_T)$$  \hspace{1cm} (2)

The parameter $m_T = \sqrt{p_T^2 + m^2}$ denotes the transverse mass of the anti-nucleon, $M_T$ the transverse mass of the anti-nucleus. Tab. 3 lists the homogeneity volumes and radii $R = \sqrt[3]{V_{hom}}$, which were derived from the coalescence coefficients by using $B_A = 1/V_{eff}^{-1}$ and Eq. 2. The radii can be compared to radii derived from $\pi^\pm\pi^\pm$ interferometry [4], i.e. in beam direction $R_{long} = 5.99 \pm 0.19$ (stat.) $\pm 0.36$ (syst.), and perpendicular to the beam direction $R_{out} = 5.39 \pm 0.18$ (stat.) $\pm 0.28$ (syst.). The radii in Tab. 3 are smaller, which can be explained by the expectation that the radii relate to the transverse mass by $R \sim 1/\sqrt{m_T}$ [10]. The $\pi$ mesons from $\pi^\pm\pi^\pm$ interferometry correspond to $0.2 \leq m_T \leq 0.5$ GeV, the anti-nuclei to $m_T \geq 1$ GeV.
In summary, ultra-relativistic $Au+Au$ collisions at RHIC were used to study production of anti-nuclei. A raw yield of 6416 Anti-$d$ and 193 Anti-$^3He$ was collected. Coalescence coefficients $B_2$ and $B_3$ were determined at a $\sqrt{s}$ which is a factor 10 higher than other experiments, and might be used as input for estimates of anti-nuclei production in the stellar medium. $B_2$ and $B_3$ were used to derive fireball radii of $\approx 4.6-5.0$ fm, which are consistent with radii from $\pi^+\pi^-$ interferometry $\approx 5.4-6.0$ fm, when taking into account different transverse mass $m_T$ of pions and anti-nuclei.

As a future outlook, STAR will resume data taking in 12/2003. In an envisaged data sample of 50,000,000 $Au+Au$ Events, one would expect an yield of $\geq 3$ Anti-$^4He$, which would be a first observation.

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