Antihelium-3 production in lead–lead collisions at 158 $A$ GeV/c

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Abstract. The NA52 experiment measured particle and antiparticle yields at 0° production angle over a wide range in rapidity in lead–lead (Pb–Pb) collisions at 158 $A$ GeV/c with a minimum bias trigger. Besides $O(10^6)$ antiprotons ($\bar{p}$) and $O(10^3)$ antideuterons (d) a total of five antihelium-3 ($\bar{3}$He) were found. The resulting invariant differential $\bar{3}$He production cross sections at $p_t \simeq 0$ GeV/c turn out to be $E \frac{d^4\sigma}{dp^4} = (2.5 \pm 1.8) \times 10^{-7}$ bc$^3$ GeV$^{-2}$ at a rapidity of $y = 3.4$ in the laboratory system and $(5.9 \pm 3.4) \times 10^{-8}$ bc$^3$ GeV$^{-2}$ at $y = 4.0$. The results are discussed in the framework of a simple coalescence model.
1. Introduction

The first observation of antihelium-3 \(^{3}\text{He}\) production in heavy ion collisions was reported by NA52 in [1]. In the meantime more data have been collected at two rapidities \(y = 3.4\) and \(4.0\) (see table 1). In this paper we present data on the \(^{3}\text{He}\) production at nearly zero transverse momentum \((p_t \sim 0)\) using the full statistics of \(O(10^{12})\) lead–lead (Pb–Pb) collisions in our experiment. The data were taken with a minimum bias trigger. No cuts on the centrality of the collisions were applied.

| Year  | Rigidity \(p/Z\) \((\text{GeV/c})\) | Incident \(\text{Pb ions}\) \((10^{10})\) | \(\text{Pb target thickness}\) \((\text{mm})\) | Identified \(^{3}\text{He}\) |
|-------|---------------------------------|---------------------------------|-----------------|------------------|
| 1994  | \(-20\)                         | 9.0                             | 4                | 1                |
| 1995  | \(-20\)                         | 25.5                            | 4                | 0                |
| 1998  | \(-20\)                         | 129.0                           | 40               | 1                |
| 1994  | \(-40\)                         | 9.6                             | 4                | 0                |
| 1995  | \(-40\)                         | 27.4                            | 4                | 0                |
| 1998  | \(-40\)                         | 145.0                           | 40               | 3                |
| 1998  | \(-40\)                         | 46.5                            | 40               | 0                |
| 1998  | \(-40\)                         | 4.9                             | 16               | 0                |
| 1998  | \(-40\)                         | 10.4                            | 8                | 0                |

The study of antinucleus production provides insight into the formation mechanism of antimatter in relativistic heavy ion collisions. There is evidence [2]–[4] that nuclei and antinuclei are predominantly produced via a coalescence mechanism. In this picture nucleons and antinucleons freeze out from a chemically and thermally equilibrated source at about 165 MeV [5, 6] (chemical freeze-out) and form nuclei and antinuclei via final state coalescence. Before nuclei and antinuclei freeze out, they are largely destroyed through collisions with surrounding particles due to their weak binding. Antinuclei are additionally affected by annihilation processes. Surviving antinuclei are mainly formed shortly before the expanding particle source reaches the temperature of about 120 MeV. If a quark gluon plasma is formed in the collision, enhanced antibaryon production is expected [7]–[9]. This should lead to an enhanced production of antinuclei. However, this effect may be diluted by the annihilation processes.
Annihilation has shown to be effective in decreasing $\bar{d}/d$ and $\bar{p}/p$ ratios with increasing baryon density in central Pb–Pb collisions [2, 4].

2. Experimental method

The NA52 experiment measured particle and antiparticle yields at $0^\circ$ production angle over a wide range in rapidity in Pb–Pb collisions at 158 $A$ GeV/$c$ [10]–[12]. It used the H6 beamline in the north area of the CERN-SPS as a single-particle, double-bend focusing spectrometer. This beamline, with a total length of 524 m from the target, can be operated to transport secondary particles in the rigidity range $5$ GeV/$c \leq p/|Z| \leq 200$ GeV/$c$, with $p$ the particle momentum and $Z$ the particle charge. The momentum analysis is performed in the vertical plane, and a momentum bite of up to 2.8% can be transported. The selection of production angles takes place in the horizontal plane by means of bending magnets. For this experiment a production angle around $0^\circ$ was chosen.

A schematic layout of the experimental set-up is shown in figure 1. The focusing spectrometer was instrumented with five segmented time of flight (TOF) hodoscopes (TOF1–TOF5) and five unsegmented scintillation counters (BT, B0 and B0–B2). The individual time resolution of the TOF counters varied between $\sigma_t = 74$ and 105 ps. The incident lead beam was measured by a fourfold segmented quartz Čerenkov counter (TOF0). Beam intensities of up to $2 \times 10^8$ ions/spill (with a duration of 5 s) were recorded. A differential (CEDAR) and three threshold (Č0, Č1 and Č2) Čerenkov counters provided additional particle identification capabilities. Multiwire proportional chambers (W1T–W5T, W2S, W3S, W0B and WSB) were used for particle tracking. A segmented scintillator/uranium calorimeter at the downstream end of the spectrometer added further particle identification capabilities and redundancy for the charge measurements. Details of the detector can be found in [13].

The particles are identified by their mass $m$ and charge $Z$ with the help of the TOF and energy loss ($dE/dx$) measurements in the five segmented scintillation hodoscopes (TOF1–TOF5) and the five unsegmented scintillation counters (BT, BS and B0–B2). The TOF measurement is made...
with respect to fast particles (mass $m_0$ and momentum $p_0$) with velocities of $\beta_0 \sim 1$. Pions were used as fast particles as they are copiously produced and are identified by the Čerenkov counters. With the help of a linear fit to the time delay information $\Delta t$ from the scintillation counters at the various detector distances $L/c$ from the target we determine the slope $\langle \Delta t / L/c \rangle$.

$$\langle \Delta t / L/c \rangle = 1/\beta - 1/\beta_0.$$  

(1)

A graphical display of the $\Delta t$ versus $L/c$ of one event is shown in figure 2. From the slope $\langle \Delta t / L/c \rangle$ and the spectrometer rigidity $p/Z$ we extract the mass to charge ratio

$$\left( \frac{m}{Z} \right)^2 = \left( \frac{p}{Z} \right)^2 \left[ \left( \langle \Delta t / L/c \rangle + \frac{1}{c^2} \right)^2 - \frac{1}{c^2} \right].$$  

(2)

The charge squared is obtained from the mean of the pulse heights of the TOF and B counters. Although the Landau distribution has a significant tail towards higher $dE/dx$ for a single counter, combining the measurement of several detectors allows us to separate the charges of the observed particles. Figure 3 shows the mean $dE/dx$ of positively charged nuclei up to $Z = +6$, corresponding to the maximum of the dynamic range of the charge measurement. This demonstrates the ability to detect positively and negatively charged objects up to a maximum charge of $|Z| = 6$.

The antinuclei detected in NA52 are $\bar{p}$, $\bar{d}$ and $\bar{^3\text{He}}$. One $^3\text{He}$ event at $-40 \text{ GeV/c}$ is presented here in detail as an example. The $dE/dx$ for this event, measured in individual counters along the beamline, is shown in figure 4 as a function of $L/c$. All the counters show an enhanced pulse height consistent with $Z = -2$. In the calorimeter at the end of the beamline the $^3\text{He}$ deposited...
1.5

Figure 3. Charge distribution at a rigidity $p/Z = +200$ GeV/c. One can clearly identify the different projectile fragments. These measurements show that NA52 can separate charges up to $|Z| = 6$.

an energy of $E = (85.8 \pm 4.4)$ GeV, which is compatible with a doubly charged object at a rigidity of $-40$ GeV/c. This $^3\text{He}$ event is the one already shown in the graphical display of figure 2. The reconstructed mass of $m = (2.72 \pm 0.14)$ GeV/c$^2$ is consistent with a $^3\text{He}$. In the multiwire proportional chambers and in the TOF hodoscopes no multiple entries were recorded excluding the presence of more than one particle in the beamline.

3. Results and discussion

Table 1 shows a summary of the data taking for the $^3\text{He}$ search. In 1998 a significant increase of the statistics was achieved compared to data from 1994 and 1995 published in [10].

We found a total of two $^3\text{He}$ at a rigidity of $-20$ GeV/c and three at $-40$ GeV/c. No antitriton $\bar{\text{t}}$ has been observed. At a rigidity of $-20$ GeV/c this can be explained by the fact that the acceptance for a singly charged particle like a $\bar{\text{t}}$ is a factor of four smaller than that of a doubly charged particle like a $^3\text{He}$. We assume the same production cross section near centre of mass rapidity ($y_{\text{cm}} = 2.9$) for $^3\text{He}$ ($y = 3.4$) and for $\bar{\text{t}}$ ($y = 2.7$) at $-20$ GeV/c. At the rigidity of $-40$ GeV/c the larger acceptance for $^3\text{He}$ is counterbalanced by the reduced $^3\text{He}$ production cross section (factor 4) at $y = 4.0$ as shown in table 2 and in figure 8. Since three $^3\text{He}$ have been
identified at a rigidity of $-40$ GeV/c, we would also have expected to find a similar number of $\bar{t}$. They should have shown up in the mass to charge spectrum of figure 5 obtained from the TOF information.

The invariant differential production cross section for particles with energy $E$ and momentum $p$ is evaluated from

$$\frac{Ed^3\sigma}{dp^3} = \frac{E}{p^3} \frac{N_S}{N_{Pb}} \frac{1}{n\alpha \epsilon},$$

with $N_S$ the number of observed secondary particles, $N_{Pb}$ the number of incident lead ions, $n = 0.033$ b$^{-1}$ cm$^{-1}$ the number of target nuclei per unit area and $\alpha$ the spectrometer acceptance. The factor $\epsilon$ accounts for the trigger and reconstruction efficiencies, which varied between $\epsilon = 0.75$ and 0.8.

The acceptance of the spectrometer $\alpha$ was deduced from the Monte Carlo simulation DECAY TURTLE [14], which takes multiple scattering into account. In this simulation a flat momentum and angular distribution of the produced particles was assumed. Figure 6 shows the iso-transmission lines at a rigidity of $-40$ GeV/c as a function of the polar angle and the momentum deviations for particles reaching counter TOF3. The integrated transmission corresponds to an acceptance of 5.45 $\mu$sr\%. In order to obtain agreement between the measured
Figure 5. Mass to charge spectrum obtained from the TOF information at a rigidity of $-40 \, \text{GeV}/c$. The particles tagged by the Čerenkov counters ($\bar{p}$, $K^-$, $\pi^-$) are shown light coloured. Antitritons would have appeared clearly separated from the antideuterons. Antihelium-3, which are not resolved here, are identified from the charge measurement as doubly charged objects.

Figure 6. Shown are the iso-transmission lines (1, 10, 50, 90 and 99%) obtained from the Monte Carlo simulation DECAY TURTLE [14] at a rigidity of $-40 \, \text{GeV}/c$ as a function of the polar angle and the momentum deviations for particles reaching counter TOF3. The integrated transmission corresponds to an acceptance of $5.45 \, \mu \text{sr}\%$.

and simulated beam profiles the acceptance was corrected by a factor of 0.67, which also turned out to be the same at a rigidity of $-20 \, \text{GeV}/c$. The acceptances finally used in the cross section calculations are $\alpha = 3.14 \, \mu \text{sr}\%$ at a rigidity of $-20 \, \text{GeV}/c$ and $\alpha = 3.60 \, \mu \text{sr}\%$ at a rigidity of $-40 \, \text{GeV}/c$. 

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Table 2. Invariant differential production cross sections and yields for $^3$He measured by NA52. Only statistical errors are shown. The rapidity of the centre of mass in the laboratory system is $y_{cm} = 2.9$.

| Rigidity (GeV/c) | Rapidity (lab) | $p_t$ bite (MeV/c) | Number of events | Cross section (b c$^3$ GeV$^{-2}$) | Yield (c$^3$ GeV$^{-2}$) |
|------------------|----------------|--------------------|------------------|-------------------------------------|--------------------------|
| $-20$            | 3.4            | 0–28               | 2                | $(2.5 \pm 1.8) \times 10^{-7}$     | $(3.0 \pm 2.2) \times 10^{-8}$ |
| $-40$            | 4.0            | 0–56               | 3                | $(5.9 \pm 3.4) \times 10^{-8}$     | $(7.2 \pm 4.2) \times 10^{-9}$ |

Figure 7. Measured number of secondary $\bar{p}$ and $\bar{d}$ per incident lead ion as a function of the target thickness. From the linear dependence we conclude that absorption and rescattering counterbalance each other.

The absorption of $^3$He in the beamline and in the target as well as additional production due to rescattering of lead fragments in the target is taken into account in the evaluation of the production cross sections. The dependence on target thickness was studied with $\bar{p}$ and $\bar{d}$ yields using targets with different thicknesses (4, 8, 16, 40 mm). The number of secondaries per incident lead ion increased linearly with the target thickness as shown in figure 7. From this we conclude that absorption and rescattering counterbalance each other. We assume in our analysis a similar behaviour for $^3$He.

We derive invariant differential yields $Y$ according to

$$Y = \frac{E d^3 \sigma}{d p^3} / \sigma_{PbPb}$$

assuming a total Pb–Pb cross section of $\sigma_{PbPb} = (8.2 \pm 2.0)$ b [15].

The resulting invariant differential $^3$He production cross sections and yields at a rigidity of $-20$ and $-40$ GeV/c are shown in table 2. Only statistical errors are shown. The systematic error is mainly due to the uncertainty of the spectrometer acceptance and is estimated to be 25% for the cross sections. The uncertainty of the total Pb–Pb cross section adds to the systematic error of the yields. The total systematic error of the yields then turns out to be 35%.
Figure 8. NA52 invariant differential $\bar{p}$, $\bar{d}$ [10] and $^3$He production cross sections versus rapidity. The closed symbols are the measured points; open symbols are mirrored at $y_{cm} = 2.9$, which is the rapidity of the centre of mass in the laboratory system. Only statistical errors are shown. The curves are drawn to guide the eye.

In figure 8 the $^3$He cross sections are shown as a function of rapidity $y$. Previously published $\bar{p}$ and $\bar{d}$ cross sections [10] are also shown in the figure. The measured points are mirrored at the centre of mass rapidity. The lines are drawn to guide the eye.

The coalescence scaling factor $B_3$ [16] for $^3$He is calculated near the centre of mass rapidity from the $^3$He yields $Y_{^3\text{He}}$ in table 2 and the antiproton yield $Y_{\bar{p}} = (0.166 \pm 0.006) c^3 \text{GeV}^{-2}$ also measured by NA52 [4]:

$$B_{3^\text{He}} = \frac{Y_{^3\text{He}}}{(Y_{\bar{p}})^3} = (6.7 \pm 4.9) \times 10^{-6} \text{GeV}^4 c^{-6}.$$ 

The antiproton yield is corrected for feeding from antilambda decays using the model of [17]. The measured $B_3$ value for $^3$He is compatible with $B_3$ for $t$ ($B_t^3 = (6.8 \pm 2.9) \times 10^{-6} \text{GeV}^4 c^{-6}$) and for $^3$He ($B_{3^\text{He}} = (2.3 \pm 1.0) \times 10^{-6} \text{GeV}^4 c^{-6}$) in accordance with the coalescence production mechanism. A compilation of coalescence scaling factors $B_3$ at different centre of mass energies $\sqrt{s}$ is shown in figure 9 including other results from Bevalac [18, 19], AGS [20]–[23] and RHIC [24]. The coalescence scaling factor $B_3$ appears to decrease with increasing energy, indicating that the source volume [3, 25, 26] is increasing.

NA52 has also measured $^3$He production in Pb + Pb collisions [10]. The ratio of $^3$He to $^3$He production cross sections in Pb–Pb collisions from NA52 can be compared to that in p–Be collisions, measured at zero degree production angle with a small acceptance focusing spectrometer [27]. Using the $^3$He cross section from this paper and our $^3$He cross sections...
from [10] we obtain a ratio of \( \frac{3\text{He}}{3\text{He}}_{\text{Pb--Pb}} = (1.4 \pm 1.1) \times 10^{-3} \) in minimum bias Pb--Pb collisions. In minimum bias p--Be collisions this ratio is \( \frac{3\text{He}}{3\text{He}}_{\text{p--Be}} = (11 \pm 7) \times 10^{-3} \) [27], scaled down from 220 to 158 GeV/c using the \( \sqrt{s} \) dependence of the \( \bar{p}/p \) ratio in p--p collisions [28] between 220 and 158 GeV/c. These ratios show no enhanced antibaryon production in Pb--Pb collisions as compared to p--Be collisions, which would be expected in the case where a quark gluon plasma was formed in Pb--Pb collisions. However, as mentioned before, a possible enhancement of antimatter production can be counterbalanced by antimatter annihilation in the baryon rich environment of Pb--Pb collisions. The observed suppression of the \( 3\text{He} \) to \( 3\text{He} \) ratio in Pb--Pb collisions relative to that in p--Be collisions may also be due to a possible contribution to the \( 3\text{He} \) production cross section from the feeding of projectile fragments.

4. Conclusions

We have presented data on \( 3\text{He} \) production at nearly zero transverse momentum using the full statistics of O(10^{12}) Pb--Pb collisions. We found a total of two \( 3\text{He} \) at a rigidity of \(-20\) GeV/c and three at \(-40\) GeV/c. This allowed us for the first time to present differential \( 3\text{He} \) production cross sections as a function of rapidity. The coalescence scaling factor \( B_3 \) calculated from the \( 3\text{He} \) and \( \bar{p} \) yields is \( B^{3\text{He}}_3 = (6.7 \pm 4.9) \times 10^{-6} \text{ GeV}^4 \text{ c}^{-6} \). A compilation of coalescence scaling factors indicates that \( B_3 \) decreases with increasing centre of mass energy, indicating that the source volume is increasing.
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