An investigation of the antinuclei and nuclei production mechanism in Pb + Pb collisions at 158 A GeV

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Abstract. We investigate the production mechanisms of p, d, t, ³He, ⁴He, ⁶Li, ⁵Π, ⁶Π and ³He in Pb + Pb collisions at 158 A GeV measured near zero transverse momentum with the NA52 experiment at the CERN SPS. We find evidence that nuclei and antinuclei in Pb + Pb collisions are mainly produced via the coalescence mechanism out of a thermalized source of hadrons, at a time close to the thermal freeze-out of hadrons corresponding to a temperature of ∼120 MeV.

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1. Introduction

The production mechanism of nuclei and antinuclei in ultrarelativistic heavy ion collisions is interesting from many points of view. Matter and antimatter production may give important experimental information on the QCD (quantum chromodynamics) phase transition from deconfined quarks and gluons to confined hadrons, a process which took place about 1 µs after the big bang in the early universe. The discovery of the latter is an outstanding goal of the heavy ion experiments [1]. In particular, antibaryon production is expected to be enhanced in a collision which goes through the QCD phase transition, as compared to one which does not [2]. However, a possible enhancement will be counterbalanced by the effect of annihilation of antibaryons in the baryon-rich environment of the collision [3]. In order to investigate the enhancement of antinuclei production, one needs to determine the amount of absorption. If nuclei and antinuclei are formed through coalescence one can use their production cross section ratios to measure the volume of the particle source from which they emerge. This offers important information on the space–time evolution of the reaction. Furthermore, one can gain additional insights into the density profile of their source [4]. From the nuclei and antinuclei production cross section ratios one obtains information about the thermal equilibration of the source and its temperature. To reach thermal equilibrium is a precondition for the formation of a quark gluon plasma (QGP). One can also learn about the dynamics of the collision, e.g. on the collective motion of the particles like the so-called transverse flow, which influences the slope of the transverse momentum spectra.

NA52 is a fixed target experiment at the CERN SPS with the main goal of searching for strangelets in 158 A GeV Pb–Pb collisions. Besides the dedicated search for strangelets [5, 6] we measure production cross sections of (anti)particle and (anti)nuclei over a wide range of rapidity (y) and near zero transverse momentum (pT) [7]–[11]. In this paper we focus on features of nucleus and antinucleus (p, p, d, d, t, 3He, 3He, 4He, 6Li) production in Pb + Pb collisions at 158 A GeV. All data are measured near zero pT. We obtained nuclei and antinuclei production...
cross sections up to \( A = 3 \) at \( y = 3.3 \) and nuclei cross sections up to \( A = 6 \) at rapidity \( y = 5.4 \).

2. Experimental method

NA52 uses the secondary beam line H6 in the north area of the SPS at CERN as a spectrometer. The set-up is shown in figure 1. A detailed description of the NA52 experimental set-up can be found in [7, 12]. The solid angle acceptance is \( \Delta \Omega = 2.2 \mu \text{sr} \) and the momentum acceptance \( \Delta p/p = 2.8\% \). The production angle was chosen to be near zero \( (p_T \sim 0) \). Incident lead (Pb) ions are counted with a fourfold segmented quartz Čerenkov counter (TOF0). The average intensity for most of the particle production measurements was \( \sim 10^7 \) ions per spill (with a spill length of 5 s). The used average intensity for the \(^3\text{He} \) production measurement was \( \sim 10^8 \) ions per spill. Particle identification is achieved by means of time of flight measurements with five eightfold segmented scintillation counters (TOF1–TOF5) and with five additional unsegmented scintillator counters (BT, B0, B1, BS, B2). Additional particle identification is provided by one differential (CEDAR) and three threshold Čerenkov counters (\( \tilde{C}0, \tilde{C}1, \tilde{C}2 \)) and by a segmented uranium/scintillator calorimeter placed at the end of the spectrometer. Several multiwire proportional chambers (W1T–W5T, W2S, W0B, W3S, WSB) were used for particle tracking. The charge of the particles was measured via their energy loss in the scintillation counters. The particle identification methods used in the NA52 experiment are described in [11, 7]. Pion identification is described in [8]. Preliminary results of NA52 shown in conferences which address certain aspects of the data analysis in detail can be found in [13]. The NA52 experimental apparatus is sensitive to all charged particles reaching the trigger counter B1. Changing the rigidity \( (p/Z) \) of the H6 beamline we can measure charged particle production over a large range of rapidity \( (y \sim 2.4–6.3) \). A 4 mm lead target, corresponding to 10% of an interaction length, was used for all the data collected at \( y = 3.3 \) with the exception of the \(^3\text{He} \) data [7], which have been taken with targets of several thicknesses up to 40 mm. The data at \( y = 5.4 \) have also been taken with targets of different thicknesses of 4, 8, 16 and 40 mm. The production cross sections were corrected for the target thickness [7]. Empty target runs were also taken for background subtraction. The trigger required at least one charged particle in the spectrometer. The dependence of the production cross sections on the impact parameter \( (b) \) of the collision was also studied for part of the data, covering the range \( b = 0–12 \) fm. The impact parameter selection was done using two lead/quartz fibre electromagnetic calorimeters (QFC) of 25 radiation lengths \( (X_0) \) with a pseudorapidity acceptance of \( 2.7 < \eta < 4.1 \), positioned 0.6 m downstream of the target [14].

3. Analysis and uncertainties

Details of the analysis of the centrality dependence of particle, antiparticle and nuclei, antinuclei yields can be found in [9]. A comparison of NA52 data on the impact parameter dependence of the particle yields with the results of other experiments can be found in [15]–[17]. The systematic error of the invariant differential cross section is estimated to be 15% mainly due to the uncertainty of the spectrometer acceptance. The \(^3\text{He} \) data have a larger systematic error of 25%, due to the higher Pb beam intensity and the change in the spectrometer optics. In order to compare production cross sections of various particles at a given rapidity some of the...
Figure 1. Schematic layout of the H6 beam line equipped with an incident beam counter (TOF0), TOF hodoscopes (TOF1-5), scintillation counters (BT, BS and B0–B2), threshold Cherenkov counters (C0–C2), a differential Cherenkov counter CEDAR, multi-wire proportional chambers (W1T–W5T, W2S, W3S, W0B and WSB), a quartz fibre calorimeter (QFC) and a hadron calorimeter at the end of the beamline. In this layout no focusing elements (quadrupoles and sextupoles) of the spectrometer are shown. Strings of bending magnets are indicated as triangles.

Table 1. Differential production cross sections of negative particles in minimum bias Pb + Pb collisions at $y = 3.3$ and near zero $p_T$. Antiprotons have been corrected for $\Lambda$ decays using the VENUS 4.12 event generator.

| Particle | Differential Cross Section ($E d^3\sigma/d^3p$) |
|----------|-----------------------------------------------|
| $\bar{p}$ | $1.361 \pm 0.25$ GeV$^{-2}$                  |
| $\bar{d}$ | $(6.6 \pm 0.73) \times 10^{-4}$ GeV$^{-2}$    |
| $^3\text{He}$ | $(2.5 \pm 1.8) \times 10^{-7}$ GeV$^{-2}$    |

particle cross sections shown here are interpolated between measured points using our rapidity distributions published in [18, 19, 10]. In particular, the $p$, $\bar{p}$, $d$, $\bar{d}$ have been interpolated at $y = 3.3$, and the $p$ and $^3\text{He}$ at $y = 5.4$. We perform the interpolation using a parametrization of the rapidity dependence of the invariant differential cross sections shown in figures 2 and 3 of [10]. The systematic error of this interpolation is small ($\sim 10\%$), as the shape of the rapidity distribution has been measured over a wide range of rapidity. Protons and antiprotons have been corrected for decays of $\Lambda$ ($\sim 30\%$ correction) and $\bar{\Lambda}$ ($\sim 50\%$ correction) using the VENUS 4.12 event generator [20]. The resulting differential production cross sections are shown in tables 1–3. Throughout this paper the error bars shown correspond to statistical errors only, unless otherwise stated.

4. Antibaryon absorption

The observed decrease of both the $\bar{p}/p$ and $\bar{d}/d$ ratios in our data [9] with increasing centrality of the collision can be understood as a result of increasing annihilation of antibaryons in the baryon-rich environment. A second observation is that the $\bar{p}/p$, $\bar{d}/d$ and $^3\text{He}/^3\text{He}$ ratios are
larger in the p + Be collisions at 220 GeV/nucleon [21] as compared to the Pb + Pb collisions at 158 A GeV (figure 2). Both data sets are taken with minimum bias trigger, at \( p_T \sim 0 \) and at midrapidity. The difference between the ratios in p + Be and Pb + Pb collisions increases with increasing particle mass as shown in figure 2. Both observations provide evidence for annihilations in Pb + Pb collisions.

We compare in the following the invariant differential yields of \( \bar{p}, p, \bar{d}, d, \bar{^3\text{He}} \) and \( ^3\text{He} \) in minimum bias p + Be [21] and Pb + Pb collisions at midrapidity and near zero \( p_T \). We derive the differential invariant yields from the differential invariant cross sections by using the following relation: \( E d^3N/dp^3 = (1/\sigma_{\text{tot}}) E d^3\sigma/dp^3 \), where \( \sigma_{\text{tot}} \) is the total reaction cross section. The total cross section for p + Be reactions at 220 GeV is assumed to be approximately equal to the total cross section for n + Be reactions at 215 GeV namely \( \sigma_{\text{pBe}} = 0.2735 \) b [22, 23]. In the following we take an estimated total Pb + Pb cross section of \( \sigma_{\text{PbPb}} = 8.2 \) b [10].

The invariant differential particle yields in minimum bias Pb + Pb and p + Be collisions and their ratios are shown in table 4 for each particle. In minimum bias Pb + Pb collisions the mean number of participant nucleons is \( 103 \pm 2 \) and in minimum bias p + Be collisions \( 2.3 \pm 0.1 \) [9]. Therefore, the participant nucleons from minimum bias Pb + Pb to minimum bias p + Be collisions scale like 103/2.3 = 45. We show in table 5 the double ratio of invariant differential particle yields \( E d^3N/dp^3 \) per participant nucleon of Pb + Pb over p + Be collisions, which should be one if scaling holds and if there is no enhancement in Pb + Pb over p + Be collisions. However, the particle yields do not scale with the number of participants, with the

Table 2. Differential production cross sections of positive particles in minimum bias Pb + Pb collisions at \( y = 3.3 \) and near zero \( p_T \). Protons have been corrected for decays of \( \Lambda \) using the VENUS 4.12 event generator.

| \( E d^3\sigma/dp^3 \) | \( E d^3\sigma/dp^3 \) | \( E d^3\sigma/dp^3 \) |
|-----------------|-----------------|-----------------|
| (b \( c^3 \text{ GeV}^{-2} \)) | (b \( c^3 \text{ GeV}^{-2} \)) | (b \( c^3 \text{ GeV}^{-2} \)) |
| p | d | \( ^3\text{He} \) |
| 17.188 ± 2.045 | 0.105 ± 0.005 | (1.84 ± 0.76) \( \times 10^{-4} \) |

Table 3. Differential production cross sections of positive particles in minimum bias Pb + Pb collisions at \( y = 5.4 \) and near zero \( p_T \). Using the VENUS 4.12 event generator it was found that the protons originating from \( \Lambda \) decays at this rapidity are a negligible fraction (below the per cent level) of the total proton yields.

| \( E d^3\sigma/dp^3 \) | \( E d^3\sigma/dp^3 \) | \( E d^3\sigma/dp^3 \) |
|-----------------|-----------------|-----------------|
| (b \( c^3 \text{ GeV}^{-2} \)) | (b \( c^3 \text{ GeV}^{-2} \)) | (b \( c^3 \text{ GeV}^{-2} \)) |
| p | d | \( ^3\text{He} \) |
| 100.0 ± 33.75 | 5.26 ± 1.56 | 0.40 ± 0.14 |
| \( ^4\text{He} \) | \( ^6\text{Li} \) | \( (2.91 ± 0.77) \times 10^{-5} \) |
Figure 2. Production cross section ratios of $\bar{p}/p$, $\bar{d}/d$ and $\bar{3He}/3He$ in $p + Be$ collisions at 220 GeV [21] and in $Pb + Pb$ collisions at 158 A GeV as a function of the particle mass are shown. They are measured near midrapidity and zero transverse momentum with a minimum bias trigger. In this plot the systematic error coming from the interpolation of the $Pb + Pb$ data points in rapidity has been taken into account.

As shown in table 5 protons and nuclei are enhanced in $Pb + Pb$ collisions as compared to the expected $N_p$ scaling. Protons appear to be enhanced by a factor of 4.49 over $p + Be$ collisions. As protons are themselves part of the initial ‘participant nucleons’ $N_p$, they are expected to scale in a similar way as $N_p$. The measured protons include those which are pair produced together with antiprotons, however our ‘net protons’ ($p - \bar{p}$) are also enhanced. This is due to the fact that $N_p$ refers to all participant nucleons in the full phase space while the protons shown here are at midrapidity. The enhancement of $d$ and $3He$ in $Pb + Pb$ collisions by much larger factors than the protons is mainly due to projectile fragmentation. This is especially pronounced near zero $p_T$. A small part of the observed nuclei enhancement originates from coalescence and can be quantified by the antinuclei enhancement factors of $\sim 3$ and 8 (table 5). The latter obviously cannot be due to projectile fragmentation, and if it were due e.g. to enhanced pair production or enhanced antimatter production, one would expect to see the same enhancement in the antiprotons.
Table 4. Invariant differential yields $E\,d^3N/dp^3$ of particles in minimum bias Pb + Pb and p + Be collisions, at midrapidity and near zero $p_T$. The last column shows their ratios. Systematic errors have been taken into account.

| Particle | Pb + Pb | p + Be | Pb + Pb/p + Be |
|----------|---------|-------|---------------|
|          | $E\,d^3N/dp^3$ (1/GeV²) | $E\,d^3N/dp^3$ (1/GeV²) |               |
| p        | 2.10 ± 0.58 | (1.06 ± 0.07) × 10^{-2} | 198 ± 57      |
| d        | (1.28 ± 0.33) × 10^{-2} | (9.54 ± 1.10) × 10^{-6} | 1342 ± 374    |
| $^3$He   | (2.24 ± 0.99) × 10^{-5} | (5.08 ± 0.73) × 10^{-9} | 4418 ± 2046   |
| $\bar{p}$ | 0.17 ± 0.05 | (4.29 ± 0.55) × 10^{-3} | 39 ± 13       |
| d        | (8.05 ± 2.19) × 10^{-5} | (5.55 ± 1.10) × 10^{-7} | 145 ± 49      |
| $^3$He   | (3.05 ± 2.32) × 10^{-8} | (6.54 ± 1.97) × 10^{-11} | 466 ± 382    |

Table 5. Ratio of invariant differential yields $E\,d^3N/dp^3$ of minimum bias Pb + Pb to p + Be collisions, at midrapidity and near zero $p_T$. The ratio has been divided by the scaling factor of 45 of participating nucleons from Pb + Pb to p + Be, to show deviations from a simple expectation. Systematic errors have been taken into account.

| Particle | $((\text{Pb} + \text{Pb})/(\text{p} + \text{Be}))/(N_{\text{pBe}}/N_{\text{PbPb}})$ |
|----------|--------------------------------------------------|
| p        | 4.41 ± 1.26                                      |
| d        | 29.8 ± 8.3                                       |
| $^3$He   | 98 ± 45                                          |
| $\bar{p}$ | 0.86 ± 0.29                                     |
| d        | 3.2 ± 1.1                                        |
| $^3$He   | 10.3 ± 8.5                                      |

5. Coalescence

5.1. Antiparticle to particle ratios

Other questions which arise are how and when the nuclei and antinuclei are produced in the course of the collision. Besides direct pair production, nuclei and antinuclei can also be produced by coalescence of p, n, $\bar{p}$, $\bar{n}$ and of other light nuclei and antinuclei. But other mechanisms such as collective antimatter production in analogy to spontaneous positron emission and vacuum decay processes in QED may also play a role [25].

If coalescence is the dominant production mechanism the following relations for the particle yields are expected to hold:

$$\frac{(\bar{p}/p)^2}{d} \sim \frac{\bar{d}}{d}$$
$$\frac{(\bar{p}/p)^3}{(\bar{p}/d)/(pd)} \sim \frac{^3\text{He}/^3\text{He}}{^3\text{He}/^3\text{He}}.$$
The results are shown in figure 3 without correction for \( \Lambda \) and \( \bar{\Lambda} \) decays and in figure 4 with this correction using the event generator VENUS [20]. Figure 3(a) shows data from minimum bias Pb + Pb collisions at 158 A GeV, at midrapidity and near zero \( p_T \), while figure 3(b) shows data from minimum bias p + Be collisions at 220 GeV/nucleon also at midrapidity and near zero \( p_T \) [21]. For the closed circles in figures 3 and 4 we assume equal numbers of neutrons and protons in the final state. The stars in the figures (noted as ‘with p/n correction’) include a correction to the number of neutrons according to \( n = p(A - Z)/Z \). This correction is only approximate since the ratio n/p may change in the course of the collision. The circles and the stars in the figures set an upper and lower limit to the n/p asymmetry correction. The coalescence prediction agrees well with the Pb + Pb data (figure 3(a)) and disagrees with the p + Be data (figure 3(b)). The \(^3\)He/\(^3\)He ratio in figure 3 agrees within the errors with the expectation that \(^3\)He and \(^3\)He are built through coalescence of antinucleons (respectively nucleons) as well as through coalescence of \( \bar{d}, \bar{p} \) (respectively \( d, p \)) shown by the triangles in figures 3(a) and (b).

In summary, figures 3 and 4 suggest that coalescence is the dominant production mechanism for nuclei and antinuclei in Pb + Pb collisions at midrapidity, while in p + Be collisions nucleon and antinucleon pairs seem to be produced mainly directly and not through coalescence. This can be understood in the following manner. Nuclei and antinuclei, produced in the initial phase of the collision long before they freeze out, have a large probability to break up through interactions due to their weak binding. Additionally, antinuclei suffer annihilation in the high baryon density. Therefore, most of the nuclei and antinuclei which survive and are measured will be produced late, namely just before they freeze out. These effects are not present in p + Be collisions due to the smaller baryon density and the smaller source volume. In the following, we will discover more evidence that this is the case.

5.2. Coalescence scaling factors

In the previous comparison of the antiparticle to particle yields with the simple coalescence model we assumed implicitly that the positive and negative particles are produced through the same mechanism and originate from the same source volume. Here we examine whether this assumption is justified, by comparing the so called coalescence factors \( B_A \) for matter and antimatter. This factor is a measure of the coalescence probability and is defined as

\[
B_A = \frac{Y_A}{(Y_{\text{proton}})^A}
\]

with \( A \) being the atomic mass and \( Y = Ed^3N/dp^3 \) the invariant differential particle yield. The obtained coalescence scaling factors for minimum bias events are listed in tables 6 and 7. As can be seen, the coalescence factors for particles and antiparticles come out to be the same within the errors. It is observed that the coalescence factors increase towards forward rapidity, suggesting a decrease also in the source volume [24]. Similarly, a decrease of the source volume with increasing rapidity is also seen in the two pion correlations [26].

Figures 5 and 6 show the coalescence scaling factors obtained from the NA52 experiment together with other experimental data from the Bevalac [27, 28], BNL [29]–[33], SPS [34]–[36] and RHIC [37] experiments. The NA52 coalescence scaling factors from \( d/p^2 \) and \( \bar{d}/\bar{p}^2 \) have been corrected for \( \Lambda \) and \( \bar{\Lambda} \) decays. The coalescence factors are similar for matter and antimatter in accordance with the assumption that nuclei and antinuclei are produced through the same coalescence mechanism. The NA52 coalescence factors for central collisions [9] agree...
Figure 3. Antiparticle to particle ratios near zero transverse momentum and at midrapidity, compared to a coalescence model prediction as a function of particle mass. (a) Data from Pb + Pb collisions at 158 A GeV and (b) from p + Be collisions at 220 GeV [21]. All data are minimum bias. Here the p and $\bar{p}$ for both data sets are not corrected for the $\Lambda$ and $\bar{\Lambda}$ decays. The data points at certain mass values are artificially spread in the mass scale to enable a better reading. In this plot the systematic error arising from the interpolation of the data points in rapidity has been taken into account.

well with the data from NA44 [35] and NA49 [36] at similar conditions as shown in tables 8 and 9. The coalescence factor is found to decrease with increasing beam energy for heavy ion collisions up to SPS energies, indicating an enhancement in the particle source volume. However, it seems to remain almost constant from SPS to RHIC energies. Due to an increase in the particle source volume, with increasing centrality the coalescence factors decrease. This is more clearly
Figure 4. Antiparticle to particle ratios near zero transverse momentum and at midrapidity, compared to a coalescence model prediction as a function of particle mass. Data are from Pb + Pb collisions at 158 A GeV. Here the p and \( \bar{p} \) have been corrected for the \( \Lambda \) and \( \bar{\Lambda} \) decays using the VENUS model [20]. The data points at certain mass values are artificially spread in the mass scale to enable a better reading. In this plot the systematic error arising from the interpolation of the data points in rapidity has been taken into account.

Table 6. Coalescence scaling factors \( B \) in minimum bias Pb + Pb collisions at \( y = 3.3 \) and near zero \( p_T \). The protons and antiprotons are corrected for feeding from \( \Lambda \) and \( \bar{\Lambda} \) decays.

| \( B_2(d/p^2) \) (GeV\(^2/c^3\)) | \( B_2(d/\bar{p}^2) \) (GeV\(^2/c^3\)) | \( B_3(\text{He}/p^3) \) (GeV\(^4/c^6\)) |
|-------------------------------|-------------------------------|-------------------------------|
| (2.91 ± 0.71) \times 10^{-3} | (2.92 ± 1.13) \times 10^{-3} | (2.44 ± 1.33) \times 10^{-6} |

| \( \bar{B}_3(\text{He}/\bar{p}^3) \) (GeV\(^4/c^6\)) | \( B_3(t/p^3) \) (GeV\(^4/c^6\)) |
|---------------------------------|-------------------------------|
| (6.67 ± 6.07) \times 10^{-6} | (7.15 ± 3.87) \times 10^{-6} |

...demonstrated in figure 7 where the coalescence factors are shown as a function of the number of participant nucleons \( N_p \) [38]. Also shown in figure 7 is the good agreement between the NA52 and NA49 results. The dotted line shows the radii obtained from \( \pi \pi \) correlations by NA49, however at a lower \( m_T \) [39].

Since nuclei and antinuclei seem to be predominantly formed through the coalescence mechanism, we can extract the volume of the particle source using a coalescence model. The model of [4] gives an estimate of the source radius for an expanding source taking flow into account. In the following we use equation (6.4) of [4] in order to calculate the source radius.
Figure 5. Compilation of coalescence scaling factors at different momentum per nucleon of the incident projectile. Data taken with minimum bias trigger (all impact parameters) are shown. The $d/p^2$ and $3He/p^3$ data ($B_2$) of NA52 are corrected for $\Lambda$ and $\bar{\Lambda}$ decays. The data points at certain mass values are artificially spread in the horizontal scale to enable a better reading.

Table 7. Coalescence scaling factors $B$ in minimum bias Pb + Pb collisions at $y = 5.4$ and near zero $p_T$. The $\Lambda$ decay correction to the protons at this rapidity is negligible.

| $B_2(d/p^2)$  | $B_3(3He/p^3)$  | $B_4(4He/p^4)$  |
|--------------|-----------------|-----------------|
| $(4.31 \pm 3.94) \times 10^{-3}$ | $(2.69 \pm 3.60) \times 10^{-5}$ | $(5.73 \pm 10.01) \times 10^{-8}$ |

$^6$Li/$p^6$ (GeV$^{10}/c^{15}$)

$(1.08 \pm 2.81) \times 10^{-12}$

from the $B_2$ coalescence factor:

$$R^3 = R_T^2 R_{\text{long}} = \frac{3\pi^{3/2}(C_d)(h/(2\pi))^3}{2m_T B_2} \exp\left(2(m_T - m)\left(\frac{1}{T_p} - \frac{1}{T_d}\right)\right).$$

(2)

In this equation $R_T$ and $R_{\text{long}}$ are the transverse and longitudinal radii extracted from two pion correlations, $(C_d)$ is an average correction factor which we take to be 0.8 from [4], $m_T = \sqrt{m^2 + p_T^2}$ and $m$ are the transverse mass and the mass of the proton respectively, and $T_p$ and $T_d$ are the inverse slopes extracted from exponential fits to the $m_T$ distributions of protons.
Figure 6. Compilation of coalescence scaling factors at different momentum per nucleon of the incident projectile. Data with a central trigger (small impact parameters, typically 5–10% of $\sigma_{\text{tot}}$) are shown. The $d/p^2$ and $\overline{d}/\overline{p}^2$ data ($B_2$) of NA52 are corrected for $\Lambda$ and $\overline{\Lambda}$ decays. The energy taken for the RHIC data is the equivalent beam energy on a fixed target. The data points at certain mass values are artificially spread in the horizontal scale to enable a better reading.

Figure 7. The coalescence factor $B_2$ ($d/p^2$) is shown as a function of the number of participant nucleons $N_p$ in $\text{Pb} + \text{Pb}$ collisions at 158 A GeV. Data from the NA49 and NA52 experiments are shown to be in good agreement. The dotted line shows the radii obtained from $\pi \pi$ correlations (HBT) by NA49, however at a lower $m_T$ [39]. Figure taken from [38]. The NA52 data are from [9].
Table 8. Comparison of the coalescence factor $B_2$ in Pb + Pb collisions at 158 A GeV between the NA44 [35] and NA52 experiments. We give the $B_2$ values for the same event centrality in per cent of the total cross section $\sigma_{tot}$ and transverse momentum ($p_T$) range. Protons are corrected for feeding from $\Lambda$ decays. Because of the symmetry of the Pb + Pb collision system the rapidity $y = 3.7$ corresponds to $y = 2.1$ in the target rapidity hemisphere.

| Experiment | $B_2$ (GeV$^2$/c$^3$) | $p_T$ | $y$ | Centrality |
|------------|------------------------|------|-----|------------|
| NA44       | $(8.2 \pm 0.5) \times 10^{-4}$ | $\sim 0$ | $1.8 < y < 2.2$ | $10%\sigma_{tot}$ |
| NA52       | $(8.21 \pm 1.37) \times 10^{-4}$ | $\sim 0$ | $y = 3.7$ | $10%\sigma_{tot}$ |

Table 9. Comparison of the coalescence factor $B_2$ in Pb + Pb collisions at 158 A GeV between the NA49 [36] and NA52 experiments. We give the $B_2$ values for the same event centrality in per cent of the total cross section $\sigma_{tot}$ and transverse momentum ($p_T$) range. Protons are corrected for feeding from $\Lambda$ decays. Because of the symmetry of the Pb + Pb collision system the rapidity $y = 3.7$ corresponds to $y = 2.1$ in the target rapidity hemisphere.

| Experiment | $B_2$ (GeV$^2$/c$^3$) | $p_T$ | $y$ | Centrality |
|------------|------------------------|------|-----|------------|
| NA49       | $(3.5 \pm 1.0) \times 10^{-4}$ | $\sim 0$ | $2.0 < y < 2.5$ | $4%\sigma_{tot}$ |
| NA52       | $(4.33 \pm 1.24) \times 10^{-4}$ | $\sim 0$ | $y = 3.7$ | $5%\sigma_{tot}$ |

and deuterons. We take the values $T_p = 330$ MeV and $T_d = 420$ MeV extracted by the NA49 collaboration in central Pb + Pb collisions at 158 A GeV [36]. However, at low $p_T$ the exponential term in formula (2) is almost one. Using $B_2$ from NA52 in table 9 we obtain a source radius of $R = 5.08 \pm 0.48$ (stat.) $\pm 0.65$ (syst.) fm. This source radius as a function of the transverse mass ($m_T$) is shown in figure 8 together with NA49 results from $\pi\pi$ correlations at rapidity 3.4–3.9 and from K$^+$K$^+$ and K$^-$K$^-$ correlations at rapidity $\sim 2–3.5$ [40]. All data in figure 8 refer to central Pb + Pb collisions. The transverse mass dependence of the measured source radii from $\pi\pi$ and K K correlations is consistent with the behaviour of a collectively expanding source [4]. The coalescence source radius turns out to be larger than the radius of $R = 3.3 \pm 0.1$ fm obtained from $\pi\pi$ correlations extrapolated to $m_T = 1$ GeV, as shown in figure 8. The difference between $R(d/p^2)$ and $R(\pi\pi)$ may be due to the uncertainties of the two methods used to extract the source volume.

5.3. The atomic mass dependence

In figures 9 and 10 the production cross sections for baryons as a function of their atomic mass ($A$) are shown for central rapidity of $y = 3.3$ and forward rapidity of $y = 5.4$. The data points are fit with a function

\[ R(d/p^2) = C(1 + m_T \beta)^{-1/2} \]

\[ R(\pi\pi) = (10.32 \pm 0.73)(1 + m_T(9.19 \pm 2.0))^{-1/2}. \]

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Figure 8. Transverse mass \( m_T = \sqrt{p_T^2 + m^2} \) dependence of the source radii extracted from \( d/p^2 \) at \( y = 3.7 \) (full point, NA52 experiment where the systematic error has been taken into account) and of those extracted from \( \pi\pi\) correlations \((R_T^2/R_L)^{1/3}\), where \( R_T \) and \( R_L \) are the radii in transverse and longitudinal direction at \( 3.4 < y < 3.9 \) and KK-correlations at \( 2.0 < y < 3.5 \) (open points, NA49 experiment) in central Pb + Pb collisions at 158 A GeV. The NA49 kaon data points are artificially spread in the transverse mass scale to enable a better reading. The NA52 point has been corrected for \( \Lambda \) decays, while it has not been corrected for the neutron/proton asymmetry. Estimation of the NA52 radius has been made using the model of [4].

\[
f = p_1/p_2^{(A-1)}
\]  

(3)

where \( p_1, p_2 \) are free parameters and \( A \) is the atomic mass. From this function the penalty factor \( p_2 \) for the production cross sections of higher mass nuclei can be extracted. The penalty factors for positively charged baryons at midrapidity comes out to be \( p_2 = 223 \pm 38 \) per baryon, with \( \chi^2/\text{DOF} = 0.91/1 \) and at forward rapidity \( p_2 = 21 \pm 2 \) with \( \chi^2/\text{DOF} = 0.94/3 \). A similar fit to the antibaryon cross sections at \( y = 3.3 \) is shown in figure 10. The obtained penalty factor is \( p_2 = 2212 \pm 676 \), with \( \chi^2/\text{DOF} = 0.07/1 \). The different penalty factors of positive and negative particles find their explanation in the different signs of their baryochemical potentials (equation (4)). The penalty factors found in our experiment come out to be higher than the ones in the AGS experiment E864 of \( p_2 = 48 \) [33]. This may be attributed to the different event centralities and/or energies of the incident ions. The fact that the positive and negative nuclei are well described by a function \( f = p_1/p_2^{(A-1)} \) supports the coalescence hypothesis.

The observation of this scaling provides the possibility to predict production cross sections for heavier mass particles.
6. Thermalization

6.1. The chemical freeze-out temperature

Assuming thermal and chemical equilibrium for baryons and antibaryons we can infer from the measured particle yields information about their freeze-out temperature \( T \) and their
baryochemical potential $\mu_B$. We can write the invariant differential production cross section for particles with a chemical potential $\mu_B$, a spin $S$ and an energy $E$ according to a Boltzmann distribution as

$$E \frac{d^3 \sigma}{dp^3} = E (2S + 1) \sigma_{\text{pPb}}^{\text{TOT}} \frac{V}{(2\pi)^3} \exp \left( -\frac{E - \mu_B}{T} \right)$$

with $V$ the volume and $T$ the temperature of the source. Furthermore, we assume that the volume and the temperature of the source is the same for all considered particles. We obtain

$$\frac{\mu_B}{T} = \frac{1}{2A} \ln \frac{E \frac{d^3 \sigma}{dp^3}(\text{antinucleus})}{E \frac{d^3 \sigma}{dp^3}(\text{nucleus})}$$

from the ratio of antinucleus to nucleus cross sections. The temperature can be derived from the ratio $R = (E \frac{d^3 \sigma}{dp_A^3})/(E \frac{d^3 \sigma}{dp_A^3})$ of the production cross sections of two different nuclei or antinuclei with atomic mass $A$ and $A'$:

$$T = \frac{-(A - A')m_N}{\ln R(A'/A)(2S_A + 1)/(2S_A + 1) + (A - A')(\mu_B/T)}$$

where $S_A$ and $S_A'$ are the spins, and $m_N$ the mass of the nucleon.

When using the $d/p$ and the $\bar{p}/p$ ratios at $y = 3.7$ with the $p$ and $\bar{p}$ corrected for $\Lambda$ and $\bar{\Lambda}$ decays we find a temperature of $T = 112 \pm 4$ (stat.) $\pm 4$ (syst.) MeV for the most central Pb + Pb collisions corresponding to $\sim$5% of the total cross section. This chemical freeze-out temperature comes out to be close to the temperature of $T = 120$ MeV which characterizes the thermal freeze-out of hadrons in central Pb + Pb collisions measured by other experiments [41]. It also is considerably lower than the temperature characterizing the chemical freeze-out of hadrons in central Pb + Pb collisions at 158 A GeV of $T \sim 170$ MeV [42, 43, 16]. This strongly supports the coalescence picture which suggests that the surviving nuclei and antinuclei are mainly formed close to the thermal freeze-out. The nuclei and antinuclei forming earlier are mostly destroyed due to breakup processes in the hadron dense environment.

The dependence of the chemical freeze-out temperature for nuclei and antinuclei on the centrality at low $p_T$ and at $y = 3.7$ was found to be small, and to be slightly decreasing for the most central collisions [9]. A similar result was found using several hadron ratios from other experiments with larger $p_T$ acceptance in [44]. We conclude that the extracted temperature, independent of the considered $p_T$ range, does not vary much with the centrality.

In the following we extract the chemical freeze-out temperature of nuclei and antinuclei in minimum bias Pb + Pb collisions. From the $\bar{d}/d$ ratio at $y = 3.7$ we find $\mu_B/T = 1.58 \pm 0.03$. Using formula (6) and the production cross section ratio $^3\text{He}/d$ at $y = 3.7$ we derive the temperature $T = 130 \pm 7$ MeV.

We also derived the chemical freeze-out temperature for antinuclei. We find $\mu_B/T = 1.267 \pm 0.09$ from the $\bar{d}/d$ ratio at $y = 3.3$. From this and the $^3\text{He}/d$ ratio at rapidity $y = 3.3$ and using formula (6) we derive the temperature $T = 137 \pm 16$ MeV.

Therefore, nuclei and antinuclei have similar freeze-out temperatures. The slightly lower freeze-out temperature at the most central collisions finds a plausible explanation in the much higher particle density which prevents freeze-out at earlier times.

An analysis of central Pb + Pb data from NA49 on $d$, $p$ and $\bar{p}$ production yields ($p$ and $\bar{p}$ at rapidity $2.4 < y < 2.8$ and $d$ at rapidity $2.0 < y < 2.5$) from [45, 36] shows a temperature of $T = 123 \pm 2$ MeV near zero $p_T$ and of $T = 135 \pm 2$ MeV when integrated over $p_T$. Therefore, the temperature near $p_T \sim 0$ is reduced by 12 MeV. The above temperature of $T = 123 \pm 2$ MeV

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6.2. Temperature from $m_T$ distributions

In the following we examine the characteristics of the thermal bath from which baryons and antibaryons separately originate. Figure 11 shows the dependence of the invariant particle and antiparticle cross sections of equation (4) divided by a factor $E(2S + 1)$ as a function of their mass $m$, which is equivalent to their transverse mass $m_T = \sqrt{m^2 + p_T^2}$ at $p_T = 0$. Furthermore, we approximate equation (4) in the following way:

\[
E \frac{d^3\sigma}{dp^3} / E(2S + 1) = c e^{-\frac{(E - \mu_B^A)/T}{}}.
\]

\[
E \frac{d^3\sigma}{dp^3} / E(2S + 1) = c e^{-\frac{(m_{T\text{cosh}} - A\mu_B)/T}{}}.
\]

\[
E \frac{d^3\sigma}{dp^3} / E(2S + 1) = c e^{-\frac{(m_{T\text{cosh}} - (m_T/\text{GeV})\mu_B)/T}{}}.
\]

\[
E \frac{d^3\sigma}{dp^3} / E(2S + 1) = c e^{-\frac{m_{T\text{cosh}} - \mu_B/\text{GeV}}{T}}.
\]

\[
E \frac{d^3\sigma}{dp^3} / E(2S + 1) = c e^{-\frac{m_{T\text{cosh}} - (-\mu_B/\text{GeV})T/\text{GeV}}{}}.
\]

Here $\mu_B$ is the baryochemical potential of the proton. The baryochemical potential of nuclei and antinuclei is $\mu_B^A = A\mu_B$. In the approximation we use (a) $A \sim m/\text{GeV}$ and (b) $m \sim m_T$ at $p_T = 0$. Furthermore, we introduce $\mu_B/T = 1.267$ extracted from the $d/d$ ratio at $y = 3.3$. From the fit to the data points (figure 11) we extract a temperature $T = 120 \pm 29 \text{ MeV}$ ($\chi^2/\text{DOF} = 1.1/1$) for antibaryons and $T = 126 \pm 6 \text{ MeV}$ ($\chi^2/\text{DOF} = 0.51/2$) for baryons at $y = 3.3$. These temperatures turn out to be identical within the errors. The difference in the slopes of positively and negatively charged particles can be explained by the different signs of the baryochemical potential for positively and negatively charged particles. This shows that thermalization and coalescence are both needed to describe the data.

The five data points of nuclei differential cross sections at $y = 5.4$ shown in figure 12 provide enough degrees of freedom in order to extract the temperature and the chemical potential separately. The resulting temperature is $T = 91 \pm 16 \text{ MeV}$ ($\chi^2/\text{DOF} = 4.2/2$) and the chemical potential $\mu_B = 676 \pm 64 \text{ MeV}$. This temperature is consistent with the temperature $T = 102 \pm 1 \text{ MeV}$ ($\chi^2/\text{DOF} = 4.2/3$) which one obtains with a fixed $\mu_B/T = 6.3$. As mentioned previously, at $y = 5.4$ a significant contribution from projectile fragmentation is expected to be present. Particles at such high rapidity and low $p_T$ do not experience many interactions leading to a lower degree of thermalization. This may be the reason for the low quality of the fit.

6.2.1. Transverse flow. The temperatures found by the thermal model fits presented here may not reflect the real thermal temperature, due to a possible transverse flow component. We
discussed the effect of the limited \( p_T \) acceptance on the NA49 data previously. Here we try to give an estimate of the latter and its effect on the temperature. In the following we assume that the deviations of the distributions from the Boltzmann approximation are due only to the presence of transverse flow. We substitute the temperature by a sum of a thermal component \( T_{\text{th}} \) and a component due to a collective velocity \( v_{\text{flow}} \) \cite{47}: \[ T_{\text{measured}} = T_{\text{th}} + m \ast v_{\text{flow}}^2. \] (7)

We fit the function \[ E \, d^3\sigma / dp^3 / (E(2S + 1)) = C \exp(-m_{T}(\cosh y - \mu_B)) / (T + m v_{\text{flow}}^2) \] (8)
to the distribution of positively charged particles at \( y = 5.4 \) as a function of \( m_T \). Here \( C \) is the normalization constant, \( \mu_B \) the baryochemical potential, \( T \) is the thermal temperature and \( v_{\text{flow}} \) is the collective flow velocity. The fit parameters come out to be \( T = 96 \pm 19 \) MeV, \( \mu_B = 661 \pm 62 \) MeV and \( v_{\text{flow}} = 0.8 \times 10^{-4} \pm 0.3 \), with \( \chi^2/\text{DOF} = 4.2/1 \).

For the particles at \( y = 3.3 \) this fit is not possible due to the smaller number of measured points. We can, however, give an estimate of the transverse flow velocity. For this purpose we perform a fit using the Boltzmann approximation of equation (8) and substitute the temperature according to equation (7). Note that here \( \mu_B / T = 1.267 \) has been introduced. The flow velocity is fixed and the only free parameters are the temperature and the normalization constant. We then change the value of \( v_{\text{flow}} \) and perform the fit again, searching for the minimum of the \( \chi^2/\text{DOF} \) from the fit. We find that for baryons at \( y = 3.3 \) the best value for the transverse flow velocity is \( v_{\text{flow}} = 0.065 \). Correspondingly, the temperature comes out to be \( T_{\text{th}} = 110 \pm 31 \) MeV, with a

**Figure 10.** Antiproton and antinuclei cross sections as a function of atomic number \((A)\) in Pb + Pb collisions at 158 A GeV taken with a minimum bias trigger near zero \( p_T \) and at \( y = 3.3 \). The data have been corrected for the decay of \( \Lambda \). The systematic errors have been quadratically added to the statistical ones. The resulting error bars are of the size of the data points. The straight lines represent a fit through the data points using the function \( f = p_1 / p_2^{(A-1)} \).
Figure 11. Proton and nuclei (a) and antiproton and antinuclei (b) cross sections divided by the energy times the spin Boltzmann factor as a function of transverse mass $m_T$ ($m_T = \sqrt{m^2_T + p^2_T}$) in Pb + Pb collisions at 158 A GeV. The data are taken with a minimum bias trigger, near zero $p_T$ and at $y = 3.3$. They are corrected for $\Lambda$ and $\bar{\Lambda}$ decays. The systematic errors have been quadratically added to the statistical ones. The straight lines represent a fit through the data points using the function $f = p_1 e^{-m_T (\text{cosh} - (\pm 1.27)T/T)}$, where $+$ holds for the positives and $-$ for the negatives. The $|\mu^\text{proton}_B|$ of 1.27 has been extracted from the $d/d$ ratio.

\[ \chi^2/\text{DOF} = 0.001/1. \] The temperatures with and without transverse flow are compatible within the errors; however, the quality of the fit is better when flow is assumed.

In order to test the above procedure we perform the same analysis with baryons at $y = 5.4$, and we find that the best value for the transverse flow velocity is for $v^\text{flow} = 0.0$ and 0.01, which
Figure 12. Proton and nuclei cross sections divided by the energy times the spin Boltzmann factor as a function of transverse mass $m_T (m_T = \sqrt{m_T^2 + p_T^2})$ in Pb + Pb collisions at 158 A GeV taken with a minimum bias trigger, near zero $p_T$ and at $y = 5.4$. The systematic errors have been quadratically added to the statistical ones. The resulting error bars are of the size of the data points. The straight line represents a fit through the data points using the function $f = p_1 e^{-m_T (\cosh y - \mu_B)/T}$, with $p_1$, $\mu_B$ and $T$ the free parameters.

both give the same $\chi^2$/DOF = 4.2/2. The temperature for $v_{\text{flow}} = 0.01$ is $T_{\text{th}} = 92 \pm 17$ MeV and the $\mu_B(p) = 673 \pm 63$ MeV. The flow is fixed to the value of 0.01. Again the temperatures with and without transverse flow come out to be the same within the errors. Note that here $\mu_B$ is a free parameter.

In conclusion, we find a nonzero transverse flow component of $v_{\text{flow}} = 0.065 \pm 0.005$ for positively charged particles at $y = 3.3$. At forward rapidity $y = 5.4$ we find a transverse flow velocity which is compatible with zero. There is no significant change in the temperature with and without transverse flow.

7. Conclusions

We measured the production of nuclei and antinuclei in Pb + Pb collisions at 158 A GeV and studied the production mechanism within the framework of thermal and coalescence models. In Pb + Pb collisions nuclei and antinuclei seem to be produced mainly through coalescence of individual or clusters of nucleons and antinucleons respectively. This picture is strongly supported by the observed scaling of the production cross sections according to $\overline{A}/A \sim (\overline{p}/p)^A$. Such a behaviour is not seen in p + Be where a different mechanism seems to dominate. We found the coalescence factors $B$ to be the same within the errors for nuclei and antinuclei showing that matter and antimatter are produced from the same size source volume. Although the coalescence factors turn out to be similar, the coalescence penalty factors of matter and antimatter derived from the mass dependence of the production cross sections are different. This is due to the
difference in sign of the chemical potentials of particles and antiparticles. From a thermal model fit to the mass dependence of the production cross sections we also find a thermal freeze-out temperature for baryons of \( T = 126 \pm 6 \text{ MeV} \) and for antibaryons of \( T = 120 \pm 29 \text{ MeV} \) for minimum bias Pb + Pb collisions at \( y = 3.3 \). From the fits to the data we do not find any significant contribution of transverse flow, which could alter the obtained temperature values. The thermal freeze-out temperatures of nuclei and antinuclei turn out to be very close to the thermal freeze-out temperatures of hadrons of \( T \sim 120 \text{ MeV} \). No enhanced antimatter production is observed in Pb + Pb as compared to p + Be collisions. This is quantified by the antiproton yield which increases like the number of participant nucleons in the collision from p + Be to Pb + Pb. However, the antideuteron and antihelium yields per participant nucleon increase from p + Be to Pb + Pb collisions as a result of an increased coalescence probability in Pb + Pb collisions. Therefore, it seems that antiprotons are better probes to investigate antimatter enhancement in heavy ion collisions. Such an enhancement would be expected if a QGP was formed in Pb + Pb collisions. However, a possible enhancement could be counterbalanced by annihilation processes in the baryon rich environment of Pb + Pb collisions. Such an effect has been observed in our previously published data [10]. Our data support the picture that the detected nuclei and antinuclei are dominantly formed via coalescence shortly before they freeze out at a temperature of \( T \sim 120 \text{ MeV} \). Those forming earlier are mostly destroyed by annihilation and break-up processes in the hadron dense environment.

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