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Impact parameter dependence of $K^\pm$, $p$, $\bar{p}$, $d$ and $\bar{d}$ production in fixed-target $Pb + Pb$ collisions at 158 GeV/nucleon

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Abstract. Nuclear matter is expected to undergo a phase transition to quark matter in ultrarelativistic heavy-ion collisions, possibly showing up as a discontinuity in the impact parameter dependence of relevant observables. Following this expectation, we have investigated the impact parameter dependence of the invariant yields of $K^\pm$, $p$, $d$, $\bar{p}$ and $\bar{d}$ in the range $\sim 2$–12 fm in fixed-target $Pb + Pb$ collisions at 158 GeV/nucleon incident energy at the CERN SPS. The particles have been measured near zero transverse momentum and in the rapidity range $y = 3.1$–4.4. In addition, the centrality dependence of the baryon chemical potential, the effective temperature and the size of the particle emitting source at freeze-out were studied. No dramatic change in the distribution of any of these variables is observed as a function of the impact parameter. The same is found for the particle yields, with the exception of the yield of charged kaons per number of nucleons participating in the collision ($N_p$), where there is an indication of a threshold behaviour at $N_p \sim 80$. 
1. Introduction

The theory of quantum chromodynamics on the lattice predicts a phase transition of confined hadronic matter into deconfined quark and gluon matter at a temperature $T_c \sim 150–200$ MeV, which could be of first order [1]. An investigation of relevant observables in heavy-ion collisions as a function of energy and/or the impact parameter of the collision could signal a possible first-order phase transition of the nuclear matter to quark and gluon matter (called the quark–gluon plasma state (QGP)) through discontinuous behaviour of the observables at the transition point. Observation of several predicted QGP signatures (for example, an increase in strange particle production, in entropy, in the volume, a suppression of $J/\Psi$ [2]) could reveal the phase transition unambiguously.

A discontinuity in the ratio of $J/\Psi$ over the Drell Yan production cross sections has been observed in $\text{Pb} + \text{Pb}$ collisions at 158 GeV/nucleon at an impact parameter of $\sim 8$ fm or at a mean number of participating nucleons $N_p \sim 140$ [3, 4]. Hence it is interesting to test other QGP signatures than the $J/\Psi$ suppression below and above this impact parameter value.

Motivated by these considerations, we have investigated the production of $K^\pm$, $p$, $d$, $\bar{p}$ and $\bar{d}$ as a function of the centrality of the collision. We have searched for sudden changes in the particle yields and in parameters such as the temperature and the size of the particle source, which can be extracted from the particle yield measurements.

In searching for evidence for the QGP phase transition, it is also interesting to compare data from $\text{Pb} + \text{Pb}$ and from hadron + nucleus collisions. This comparison can disentangle new phenomena in heavy-ion collisions. We have compared the NA52 data from $\text{Pb} + \text{Pb}$ collisions with those from $p + \text{Be}$ collisions at 450 GeV/nucleon [5], which were rescaled to 158 GeV/nucleon. The $p + \text{Be}$ and $\text{Pb} + \text{Pb}$ data presented here have both been measured using the same experimental apparatus and cover a similar phase space acceptance.

Preliminary results of this study were published in [6]–[9]. Results on particle and nuclei production in minimum-bias $\text{Pb} + \text{Pb}$ collisions at 158 GeV/nucleon measured with the same phase space acceptance as the results of the present paper were published in [10, 11].
2. Experimental set-up

The set-up of the NA52 experiment is shown in figure 1. The secondary beam line H6 in the north area of the SPS at CERN is used as a spectrometer [12]. The solid angle acceptance is $\Delta \Omega = 2.2 \, \mu$sr and the momentum acceptance is $\Delta p/p = 2.8\%$. Incident lead ions are counted with a fourfold segmented quartz Čerenkov counter (TOF0).

Particle identification is achieved by means of time-of-flight measurements with five eightfold segmented (TOF1–TOF5) and three non-segmented scintillator counters (B0–B2). Additional particle identification is provided by one differential (CEDAR) and three threshold Čerenkov counters ($\tilde{\text{C}}0–\tilde{\text{C}}2$) and a longitudinally segmented uranium/scintillator calorimeter of seven interaction lengths ($\lambda_{\text{int}}$) placed at the end of the spectrometer. Seven multiwire proportional chambers (W1T–W5T, W2S, W3S) were used for position measurements. The charge was measured by the energy loss of the particles in the scintillation counters. The particle identification methods used in the NA52 experiment are described in [10,11].

During the 1995 run two lead/quartz fibre electromagnetic calorimeters (QFC) of 25 radiation lengths ($X_0$) with pseudorapidity acceptance of $2.7 < \eta < 4.1$, positioned 0.6 m downstream of the target were used for impact parameter selection [13,14]. The spectrometer trigger required a coincidence between the TOF2 and B1 counters. A random trigger with respect to the beam, running independently of the spectrometer trigger during the spill was also used. This trigger allowed us to acquire a separate set of calorimeter data without any biases caused by the requirement of the spectrometer trigger. A 4 mm lead target, corresponding to 10% of an interaction length, was used. Empty target runs were also taken for background subtraction.

3. Centrality dependence of invariant particle yields

The invariant particle yields have been measured near zero transverse momentum and are presented as a function of the mean number of nucleons participating in the collision ($N_p$). This allows for a comparison with the results of other experiments measuring similar observables [3,15]. The mean number of participant nucleons in the event has been deduced by comparing the energy spectrum measured with the lead/quartz fibre calorimeter (figure 2(a)), with the energy spectrum of $\pi^0 \rightarrow \gamma\gamma$ produced in Pb–Pb collisions and simulated with the event...
Figure 2. Cross section as a function of energy seen in the lead/quartz fibre calorimeter in Pb + Pb collisions at 158 GeV/nucleon (a). The calorimeter threshold was set at ∼ 20 GeV. In (b) the cross section as a function of energy for \( \pi^0 \rightarrow \gamma \gamma \) produced in Pb + Pb collisions at 158 GeV/nucleon, simulated with the VENUS 4.12 model [16] is shown. The lines and numbers in both distributions indicate the selected centrality regions for the analysis (for results see table 1).
Figure 3. VENUS 4.12 simulation of the mean number of participating nucleons as a function of the energy of $\pi^0 \rightarrow \gamma\gamma$ seen in the QFC calorimeter.

Table 1. Cross section $\sigma_{\text{cut}}$, mean number of participant nucleons in the collision $\langle N_p \rangle$ and mean impact parameter $\langle b \rangle$ for the five centrality bins illustrated in figure 2 and used in tables 4 and 5 as well as in most figures. $\sigma_{\text{cut}}$ is the cross section of each centrality region, defined as $\sigma_{\text{cut}} = \int_{E_{\text{min}}}^{E_{\text{max}}} (d\sigma/dE) dE$. The first line of the table corresponds to minimum-bias Pb+Pb collisions (no centrality cut) and the corresponding cross section has been estimated [17] from a parametrization of experimental data taken from [18]. The errors shown are the statistical errors, while the values in parentheses are the standard deviations of the distributions of $N_p$ and $b$ in the considered centrality ranges.

| Centrality cut | $\sigma_{\text{cut}}$ (barn) | $\langle N_p \rangle$ | $\langle b \rangle$ (fm) |
|----------------|-----------------------------|-----------------------|------------------------|
| No cut         | 8.2 ± 2.0                   | 103 ± 2               | 10.25 ± 0.09           |
| 1              | 2.483 ± 0.034               | 62.5 ± 0.5 (41.7)     | 11.00 ± 0.02 (1.7)    |
| 2              | 1.379 ± 0.019               | 149.3 ± 0.9 (58.7)    | 8.15 ± 0.02 (1.6)     |
| 3              | 0.835 ± 0.013               | 236.8 ± 1.2 (63.6)    | 5.81 ± 0.03 (1.7)     |
| 4              | 0.505 ± 0.010               | 297.8 ± 1.3 (55.5)    | 4.13 ± 0.04 (1.6)     |
| 5              | 0.253 ± 0.001               | 336.3 ± 1.6 (42.6)    | 3.02 ± 0.05 (1.4)     |

expected to be small and were neglected. The energy spectrum was not corrected for the energy leakage in the calorimeter. This is taken into account in the estimation of the systematic error (see the later discussion).

We have chosen five centrality regions in the measured energy distribution as indicated by lines in figure 2(a) and numbered from 1 (the most peripheral events) to 5 (the most central events). The corresponding centrality regions in the VENUS $\pi^0$ energy spectrum have been...
found by demanding the integral over each centrality interval

$$\sigma_{\text{cut}} = \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} \frac{d\sigma}{dE} \, dE}{E_{\text{max}} - E_{\text{min}}}$$

(1)

to be the same in the data and in the simulation. The resulting cross section, the mean number of participant nucleons in the collision ($\langle N_p \rangle$) and the mean impact parameter ($\langle b \rangle$) of each centrality region are shown in tables 1–3 for three different choices of energy intervals. In table 1 $\langle N_p \rangle$ and $\langle b \rangle$ for minimum-bias Pb + Pb collisions taken from the VENUS event generator are also shown as well as the total cross section for minimum-bias Pb + Pb collisions estimated [17] from a parametrization of experimental data taken from [18]. This centrality determination method does not depend on the absolute energy scale. The standard deviations ($\sigma$) of the distributions

### Table 2. Mean number of participants $\langle N_p \rangle$ and mean impact parameter $\langle b \rangle$ for the 10 GeV wide bins in energy, shown with full stars in figure 6. The errors shown are the statistical errors. The values in parentheses are the standard deviations of the distributions of $N_p$ and $b$ in the considered energy intervals.

| Centrality cut | $\langle N_p \rangle$ (stat) | $\langle b \rangle$ (stat) |
|----------------|-----------------------------|---------------------------|
| 1              | 36.6 ± 0.6 (27.2)           | 12.12 ± 0.03 (1.5)        |
| 2              | 47.2 ± 0.8 (31.4)           | 11.56 ± 0.04 (1.4)        |
| 3              | 58.8 ± 1.0 (34.0)           | 11.07 ± 0.04 (1.4)        |

### Table 3. Mean number of participants $\langle N_p \rangle$ and mean impact parameter $\langle b \rangle$ for the 30 GeV wide bins in energy, shown with open stars in figures 6 and 13, respectively, and with open triangles in figure 4. The values in parentheses are the standard deviations of the distributions of $N_p$ and $b$ in the considered energy intervals.

| Centrality cut | $\langle N_p \rangle$ (stat) | $\langle b \rangle$ (stat) |
|----------------|-----------------------------|---------------------------|
| 1              | 45.4 ± 0.5 (31.6)           | 11.75 ± 0.04 (0.83)       |
| 2              | 81.1 ± 0.8 (40.7)           | 10.49 ± 0.04 (0.75)       |
| 3              | 110.6 ± 1.1 (47.3)          | 9.36 ± 0.04 (0.70)        |
| 4              | 143.0 ± 1.4 (53.1)          | 8.64 ± 0.05 (0.71)        |
| 5              | 166.5 ± 1.6 (55.1)          | 7.86 ± 0.05 (0.62)        |
| 6              | 193.6 ± 1.7 (58.3)          | 7.12 ± 0.06 (0.63)        |
| 7              | 217.1 ± 2.0 (60.9)          | 6.61 ± 0.07 (0.71)        |
| 8              | 242.6 ± 2.1 (59.3)          | 5.90 ± 0.07 (0.77)        |
| 9              | 266.4 ± 2.2 (60.3)          | 5.28 ± 0.07 (0.73)        |
| 10             | 282.2 ± 2.3 (56.3)          | 4.95 ± 0.07 (0.62)        |
| 11             | 294.6 ± 2.4 (55.2)          | 4.55 ± 0.09 (0.88)        |
| 12             | 317.3 ± 2.4 (49.6)          | 3.63 ± 0.10 (0.75)        |
| 13             | 324.1 ± 2.3 (44.1)          | 2.69 ± 0.12 (0.92)        |
| 14             | 340.2 ± 2.5 (39.2)          | 2.61 ± 0.16 (1.06)        |
| 15             | 340.2 ± 3.6 (44.1)          | 2.02 ± 0.16 (0.96)        |
| 16             | 351.7 ± 3.6 (33.3)          | 2.25 ± 0.20 (0.65)        |
The yields were not corrected for reinteractions in the target. The correction for absorption of incident ions in the target, for the spectrometer acceptance, for losses due to decay, for elastic and inelastic interactions in the beamline, for particle absorption in the target, and for the reconstruction efficiency. Pile up effects in the incident ion counting were estimated and corrected for by using the pulse height information of the TOF Čerenkov counter. The yields have been further corrected for empty target contributions. The correction for $\Lambda$ and $\Delta$ decay corrections have been performed using VENUS 4.12 [16].

| Centrality cut | $p$ | $y = 3.7$ | $p$ | $y = 3.7$ | $p$ | $y = 3.7$ |
|----------------|-----|----------|-----|----------|-----|----------|
|                | Uncorrected | Corrected for decays | $\Lambda$ decay | Corrected for $\Lambda, \Delta$ decay |
| 1              | 11.70 ± 0.49 | 8.81 ± 0.42 | 5.01 ± 0.24 |
| 2              | 30.09 ± 0.95 | 22.90 ± 0.82 | 12.22 ± 0.44 |
| 3              | 44.07 ± 1.40 | 33.27 ± 1.19 | 16.92 ± 0.62 |
| 4              | 61.43 ± 2.11 | 46.44 ± 1.75 | 22.98 ± 0.88 |
| 5              | 71.26 ± 3.06 | 53.80 ± 2.52 | 26.29 ± 1.25 |

| | $p$ | $y = 4.4$ | $p$ | $y = 4.4$ |
|----------------|-----|----------|-----|----------|
|                | Uncorrected | Corrected for decays | $\Lambda$ decay | Corrected for $\Lambda, \Delta$ decay |
| 1              | 18.45 ± 0.74 | 13.89 ± 0.64 | 7.89 ± 0.36 |
| 2              | 43.72 ± 1.34 | 33.27 ± 1.17 | 17.75 ± 0.63 |
| 3              | 60.96 ± 1.87 | 46.03 ± 1.62 | 23.41 ± 0.83 |
| 4              | 77.28 ± 2.58 | 58.42 ± 2.16 | 28.90 ± 1.08 |
| 5              | 78.29 ± 3.26 | 59.11 ± 2.70 | 28.89 ± 1.34 |

| | $\bar{p}$ | $y = 3.7$ | $\bar{p}$ | $y = 3.7$ | $\bar{p}$ | $y = 3.7$ |
|----------------|-----|----------|-----|----------|-----|----------|
|                | Uncorrected | Corrected for decays | $\Lambda$ decay | Corrected for $\Lambda, \Delta$ decay |
| 1              | 0.937 ± 0.038 | 0.529 ± 0.038 | 0.287 ± 0.021 |
| 2              | 2.041 ± 0.064 | 1.059 ± 0.059 | 0.551 ± 0.033 |
| 3              | 2.586 ± 0.082 | 1.290 ± 0.074 | 0.621 ± 0.041 |
| 4              | 3.375 ± 0.116 | 1.707 ± 0.097 | 0.837 ± 0.052 |
| 5              | 3.752 ± 0.162 | 1.932 ± 0.131 | 0.938 ± 0.069 |

The invariant differential particle yields have been corrected for empty target contributions. This correction is seen to decrease with the centrality. The particle yields have been further corrected for absorption of incident ions in the target, for the spectrometer acceptance, for losses due to decay, for elastic and inelastic interactions in the beamline, for particle absorption in the target, and for the reconstruction efficiency. Pile up effects in the incident ion counting were estimated and corrected for by using the pulse height information of the TOF Čerenkov counter signals. The yields were not corrected for reinteractions in the target. The correction for $p, \bar{p}$ originating from decays of $\Lambda, \Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-}$ and their antiparticles were performed using VENUS 4.12.

New Journal of Physics 1 (1999) 22.1–22.23 (http://www.njp.org/)
Table 5. Invariant differential particle yields \((2\pi E \, d^3 N / dp^3)\) in \(\text{Pb} + \text{Pb}\) collisions at 158 GeV/nucleon, near zero transverse momentum, as a function of rapidity and centrality.

| Centrality cut | \(d\) \(y = 3.1\) | \(d\) \(y = 3.7\) | \(\bar{d}\) \(y = 3.1\) |
|---------------|-----------------|-----------------|-----------------|
| 1             | 0.028 ± 0.009   | 0.058 ± 0.011   | (8.01 ± 4.06)\(10^{-4}\) |
| 2             | 0.081 ± 0.017   | 0.134 ± 0.018   | (6.33 ± 3.83)\(10^{-4}\) |
| 3             | 0.119 ± 0.025   | 0.196 ± 0.027   | (7.32 ± 5.15)\(10^{-4}\) |
| 4             | 0.188 ± 0.041   | 0.282 ± 0.042   |                  |
| 5             | 0.171 ± 0.060   | 0.200 ± 0.054   |                  |

| \(\bar{d}\) \(y = 3.7\) | \(K^+\) \(y = 4.4\) | \(K^-\) \(y = 4.4\) |
|-----------------|-----------------|-----------------|
| 1               | (3.00 ± 0.94)\(10^{-4}\) | 10.39 ± 0.72   | 6.29 ± 0.25    |
| 2               | (2.97 ± 0.99)\(10^{-4}\) | 34.08 ± 1.46   | 17.18 ± 0.54   |
| 3               | (2.57 ± 1.15)\(10^{-4}\) | 52.27 ± 2.29   | 27.69 ± 0.88   |
| 4               | (5.11 ± 2.08)\(10^{-4}\) | 75.07 ± 3.52   | 40.75 ± 1.39   |
| 5               | (2.03 ± 2.12)\(10^{-4}\) | 88.74 ± 5.55   | 47.73 ± 2.03   |

The systematic error in the mean number of participant nucleons is estimated to be about 13%. It arises from the uncertainty in the determination of the geometrical acceptance of the calorimeter (\(\sim 5\%\)), from the systematic error of the absolute normalization and shape (\(\sim 5\%\)) and the empty target correction (\(\sim 5\%\)) of the energy distribution of the calorimeter as well as from differences in the shape of the distribution in the data and the simulation (\(\sim 10\%\)). The latter error was determined by arbitrarily adjusting the energy scale of figure 2(b) in such a way that the spectrum overlaps with that in figure 2(a). After this adjustment the two spectra differed by less than 10% from the mean value of the two.

We also estimated the mean number of participants using the Glauber model in the way it was implemented by the experiment NA50 [19, 20]. This method is based on the assumption that the transverse energy is proportional to the number of participants. This assumption does not hold for very large number of participants [20]. The prediction of the model of [20] is compared with the data in figure 2(a). The mean number of participants extracted from our data using the Glauber and the VENUS model differ by less than 12% from their mean value, for a number of participants less than \(\sim 250\). A direct comparison of the data presented here with the data of NA50 [3] hence seems justified. Finally, the VENUS model was used throughout the analysis of this paper.

The systematic error of the invariant particle yields due to uncertainties in the energy distribution measured with the calorimeter is estimated to be \(\sim 7\%\), the uncertainty due to the spectrometer acceptance is \(\sim 15\%\) and the uncertainty due to the empty target contribution correction is \(\sim 5\%\). The systematic error of the cross sections integrals over the centrality intervals due to uncertainties in the energy distribution is estimated to be \(\sim 5\%\), while the uncertainty due to the empty target contribution correction is \(\sim 5\%\). The resulting total systematic error for the particle yields is \(\sim 17\%\) and for the cross section integrals over the centrality bins is \(7\%\). In the figures and tables only the statistical errors are shown.
The invariant differential particle yields for each of the five centrality regions are listed in tables 4 and 5. The transverse momentum ($p_T$) acceptance of the particles ranges from zero to a maximum $p_T$ value, which is different for each rigidity and can be calculated as $p_T(\text{max}) \sim 0.0013p$, where $p$ is the momentum of the particle (see [21] for a discussion of the spectrometer acceptance). Figures 4–6 show the invariant yields of $p$, $\bar{p}$, $d$ and $\bar{d}$ at rapidity $y = 3.7$ and of $K^\pm$ and $p$ at $y = 4.4$, divided by the mean number of participant nucleons ($N_p$) as a function of the latter. The data are shown in five and/or in 16 centrality bins of tables 1 and 3. The three centrality bins shown in figure 6 as full stars are those listed in table 2. Due to lack of events the yields of antideuterons at rapidity $y = 3.1$ were measurable only in the first three centrality bins (figure 8 and table 5).

For comparison the data measured in $p + \text{Be}$ interactions are also shown in figure 6. They were measured at 450 GeV/nucleon by the NA56 experiment using the NA52 apparatus [5]. The systematic error on the particle yields in $p + \text{Be}$ interactions is between 5 and 10% depending on
Figure 5. Invariant yields of (a) $d$ and (b) $\bar{d}$ in Pb + Pb collisions at 158 A GeV near zero $p_T$ and at $y = 3.7$, divided by the mean number of participant nucleons $N_p$, as a function of $N_p$. 

the beam momentum [5]. It is smaller compared with the NA52 measurements, because NA56 used different beam line conditions with smaller acceptance uncertainties. The data were rescaled to 158 GeV/nucleon using the energy dependence of measured total particle multiplicities in $p+p$ collisions [22]. The $p$ + Be data are compared with the Pb + Pb data in the same ($y/y_{beam}$, $p_T$) acceptance. The mean number of participant nucleons for $p$ + Be collisions was estimated with VENUS 4.12 to be $\sim 2.3 \pm 0.1$. The total cross section for $p$ + Be interactions was taken from [23] to be 0.268 barn (for energies between 80 and 240 GeV). Figures 7–9 show the $\bar{p}/p$, $\bar{d}/d$ and the $K^+/K^−$ production yield ratios as a function of centrality.

4. Centrality dependence of the temperature and chemical potential

Under the assumption that local thermodynamic equilibrium is established in Pb + Pb collisions in the centrality region investigated, we can estimate the effective temperature ($T$) and the baryon
Figure 6. Dependence of the $K^\pm$ invariant yields in $Pb + Pb$ collisions at 158 A GeV near zero $p_t$ divided by the mean number of participant nucleons $N_p$ from $N_p$. For comparison the data (full stars) are also shown with a smaller bin size (see table 2). The $p + Be$ data were measured at 450 GeV/nucleon [5] and have been rescaled to 158 GeV/nucleon (see text) and are compared with the $Pb + Pb$ data at the same $p_T$ and $y/y_{beam}$.

The chemical potential ($\mu_B$) from the measured particle ratios using a simple thermodynamic model. According to Boltzmann statistics, the invariant differential cross sections can be written as

$$E \frac{d^3\sigma}{dp^3} = \sigma_{Pb+Pb} E \frac{2S + 1}{h^3} V e^{-(E-\mu_B/T)}$$

where $\sigma_{Pb+Pb}$ is the total cross section of $Pb + Pb$ collisions at 158 GeV/nucleon, $S$ is the spin of the particle, $\mu_B$ is the baryon chemical potential and $V$ is the volume of the particle source. Under the assumption that $V$ is the same for all particles, one can evaluate the ratio of the chemical potential to the temperature ($\mu_B/T$) at freeze-out from the $\bar{p}/p$ and $\bar{d}/d$ cross section ratios. We assume that $\mu_A = -\mu_A = -A\mu_B$, where $A$ and $\overline{A}$ are the nucleon numbers of particles and antiparticles, respectively.
Figure 7. Dependence of the $p/p$ ratio of the mean number of participant nucleons in Pb + Pb collisions at 158 A GeV near zero $p_T$ and at $y = 3.7$. The $\Lambda$ and $\Delta$ correction is performed using VENUS 4.12 [16]

From the measured cross section ratios $d/p$ or $\bar{d}/\bar{p}$ and from the $\mu_B/T$ determined from equation (2), assuming that we can apply this model to $d$ and $\bar{d}$, we can evaluate the effective temperature:

$$T = \frac{(A_1 - A_2)m}{\ln[(E(d^3\sigma/dp^3_{A_1}))/E(d^3\sigma/dp^3_{A_2})](A_2/A_1)((2S_{A_2} + 1)/(2S_{A_1} + 1)) + (A_1 - A_2)\mu_B/T}$$

(3)

where $A_1$ and $A_2$ are the mass numbers of $d$ and $p$ or of $\bar{d}$ and $\bar{p}$, $m$ is the nucleon mass and $S$ is the spin. The minus sign in the denominator holds for matter and the plus sign for antimatter. Knowing $T$ one can then extract $\mu_B$. The resulting $\mu_B/T$ extracted from $p/p$ and $\mu_B$ and $T$ from the $d/p$ ratios at $y = 3.7$ are displayed in figures 10 and 11 as a function of $N_p$. The same

New Journal of Physics 1 (1999) 22.1–22.23 (http://www.njp.org/)
Figure 8. Dependence of the $\bar{d}/d$ ratio of the mean number of participant nucleons in Pb + Pb collisions at 158 A GeV near zero $p_T$ and at (a) $y = 3.7$ and (b) $y = 3.1$.

parameters extracted from the $\bar{d}/d$ and $\bar{d}/\bar{p}$ ratios agree with the values shown in the figures 10 and 11 within the errors.

5. Centrality dependence of the source size

Assuming that at $y = 3.7$ deuterons are created by nucleon coalescence rather than by projectile fragmentation and that the phase space distributions of $n$ and $\pi$ is similar to that of $p$ and $\bar{p}$, it follows that the ratio of deuteron yield to the square of the proton yield ($d/p^2$) (the same for antiparticles) gives a measure of the probability that nucleons coalesce to form a deuteron. This probability depends on the nucleon distributions in phase space and in the configuration space, since only nucleons near to each other and with similar momentum can coalesce to a nucleus. The probability for the nucleons to be close enough to form a deuteron is for a given number of initial nucleons inversely proportional to the volume of the particle

New Journal of Physics 1 (1999) 22.1–22.23 (http://www.njp.org/)
Figure 9. Dependence of the $K^+/K^-$ ratio of the mean number of participant nucleons in Pb + Pb collisions at 158 A GeV near zero $p_T$ and $y = 4.4$.

Therefore, the $d/p$ and $\bar{d}/\bar{p}$ ratios are inversely proportional to the volume of their source.

Figure 12 shows the $d/p$ and $\bar{d}/\bar{p}$ ratios in Pb + Pb collisions at 158 GeV/nucleon at $y = 3.7$ and near zero $p_T$. The ratios are found to decrease with increasing number of participating nucleons, reflecting the increasing source size. This behaviour is in qualitative agreement with the centrality dependence of the same yield ratios measured in Si + A reactions at 11 GeV/nucleon [24]. The $d/p$ and $\bar{d}/\bar{p}$ ratios are compatible within errors. Furthermore, we can extract the size of the source from the $d/p$ and $\bar{d}/\bar{p}$ ratios using a coalescence model. The model used for the calculation of the source size [25, 26] assumes local thermal equilibrium and uses a Gaussian shape to describe the nucleon density distribution in space. The root mean square radius of the source in the rest frame of the proton and the neutron is given by

$$R = \left[ \frac{3}{4} \frac{\hbar^2}{2 \pi^2} \frac{m_d}{m_p} \left( \frac{E d^3 N/dp^3}{dp} \right)_d \frac{A_{Pb} - Z_{Pb}}{Z_{Pb}} \right]^{1/3}$$ (4)
Figure 10. (a) The baryochemical potential $\mu_B$ over the temperature $T$ extracted from the $p/p$ ratio and (b) $T$ extracted from the $d/p$ ratio, at $y = 3.7$ and near zero $p_T$ in $Pb+Pb$ collisions at 158 A GeV, as a function of the mean number of participant nucleons. $p$ and $\bar{p}$ have been corrected for $\Lambda$, $\bar{\Lambda}$, $\Delta$ and $\bar{\Delta}$ decays [16].

![Graph showing baryochemical potential and temperature](image)

where $m_d$ and $m_p$ are the masses of the $d$ and $p$ or $\bar{d}$ and $\bar{p}$, respectively. The factor $(A_{Pb} - Z_{Pb})/Z_{Pb}$, where $A_{Pb}$ and $Z_{Pb}$ are the nucleon and atomic numbers of a lead nucleus, accounts for the difference in the proton and neutron number in the lead nuclei, which, however, may change in the final state of the collision through interactions. This correction factor increases the radii by $\sim 15\%$.

Figures 13 and 14 show the calculated source radii without (figure 13) and with (figure 14) corrections for $p$ or $\bar{p}$ coming from $\Lambda$, $\bar{\Lambda}$, $\Delta$ and $\bar{\Delta}$ decays. In figure 13(a) we also show the results when 16 centrality bins are used (open stars). The full star point at $N_p = 103$ in figure 13 is extracted from the minimum-bias $Pb+Pb$ data sample. As is seen from figure 14, the particle and antiparticle data both give a source radius of $\sim 6.5$ fm for the most central events, after corrections for the $\Lambda$ and $\bar{\Lambda}$ decays. An additional correction for the $\Delta$ decays decreases the radii to about 4 fm. However, it is unclear whether part of the nucleons originating from $\Delta$ decays...
Figure 11. The baryochemical potential $\mu_B$ extracted from the $\mu_B/T$ and $T$ values shown in figure 10 at $y = 3.7$ and near zero $p_T$ in Pb + Pb collisions at 158 A GeV, as a function of the mean number of participant nucleons.

could also contribute to the formation of deuterons. An additional uncertainty comes from the $\Delta$ and $\Lambda$ resonance production model used in the VENUS event generator. Experimental $\Lambda$ production [27] turns out to be \sim 40\% larger than VENUS. We did not use the experimental data for this correction since they are still preliminary. In order to study the $N_p$ dependence of the source radius and to compare it with model predictions [28,29] we parametrized the radius as $R \propto N_p^\alpha$ and fitted this function to the data points in figures 13 and 14, with $\alpha$ as a free parameter. The results of the fit are shown in table 6.

6. Discussion

The $\bar{d}$ yields increase towards midrapidity independent of centrality as expected. The production of $\bar{p}$ and $\bar{n}$ and therefore of $\bar{d}$ is largest near $y_{cm}$, where the available energy for antiparticle production has a maximum. The same trend is observed for $\bar{p}$ and $\bar{d}$ in minimum-bias Pb + Pb collisions at 158 GeV/nucleon [10].

The proton and deuteron invariant yields at rapidity 3.7 increase almost linearly with the mean number of participant nucleons $N_p$, (figures 4 and 5). One would expect that protons increase linearly or slightly more than linearly with $N_p$, since most of the protons are inherited
Figure 12. $d/p^2$ and $\bar{d}/\bar{p}^2$ invariant differential yield ratios in $\text{Pb}+\text{Pb}$ collisions at 158 A GeV as a function of the number of participant nucleons $N_p$. The decay corrections were performed using [16].

Table 6. Results of the fit of the function $R = p_1 N_p^{\alpha}$ to the radii as a function of the number of participant nucleons displayed in figures 13 and 14, with $p_1$ and $\alpha$ as free parameters.

|                | $p_1(d/p^2)$ (fm) 5 bins | $\alpha(d/p^2)$ 5 bins | $p_1(\bar{d}/\bar{p}^2)$ (fm) 5 bins | $\alpha(\bar{d}/\bar{p}^2)$ 5 bins |
|----------------|--------------------------|------------------------|--------------------------------------|-------------------------------------|
| Uncorrected data | 0.70 ± 0.20              | 0.38 ± 0.05            | 0.55 ± 0.30                          | 0.47 ± 0.09                         |
| Corrected for $\Lambda$, $\bar{\Lambda}$ decay | 0.58 ± 0.17              | 0.38 ± 0.05            | 0.43 ± 0.27                          | 0.43 ± 0.10                         |
| Corrected for $\Lambda$, $\bar{\Lambda}$ and $\Delta$, $\bar{\Delta}$ decay | 0.51 ± 0.15              | 0.32 ± 0.05            | 0.35 ± 0.22                          | 0.38 ± 0.10                         |
| $p_1(d/p^2)$ (fm) 16 bins |                        |                        |                                      |                                      |
| Uncorrected data | 0.77 ± 0.21              | 0.35 ± 0.05            |                                      |                                      |
Figure 13. The source radius extracted from (a) $d/p^2$ and (b) $\bar{d}/\bar{p}^2$ yield ratios at $y = 3.7$ and near zero $p_T$, as a function of the mean number of participant nucleons in Pb + Pb collisions at 158 A GeV. In (a) the results using 16 centrality bins are also shown as open stars. The full stars at $N_p \sim 10^3$ are extracted from the minimum-bias Pb + Pb data sample. The radii were extracted using the model [25]. The displayed curves are the results of the fit of the function $R \sim N_p^\alpha$ (see table 6 for the results).

from the participating protons of the lead nuclei and only a small part is due to direct $p$ and $\bar{p}$ production. The expectation for the centrality dependence of deuterons is less straightforward, since their production through coalescence may also depend on parameters other than $N_p$.

The $\bar{p}$ and $\bar{d}$ yields divided by the number of participant nucleons $N_p$, shown in figures 4 and 5 decrease with increasing $N_p$. This behaviour, as well as the decrease of the $\bar{p}/p$ and the $\bar{d}/d$ yield ratios with increasing centrality (figures 7 and 8) indicates larger $p$ and $d$ absorption with higher baryon density.

The $K^+/K^-$ ratio at $y = 4.4$ does not change significantly as a function of the centrality (figure 9). A similar behaviour of this ratio has been measured in Au+Au collisions at 10.8 A GeV [30].

New Journal of Physics 1 (1999) 22.1–22.23 (http://www.njp.org/)
There is an indication of a deviation from a linear behaviour in the \( K^+/N_p \) ratio shown in figure 6 in the region below \( N_p \sim 80 \). The observation of a nearly linear behaviour above \( \sim 80N_p \) could be interpreted as an onset of equilibration of kaons. This, however, seems to be more pronounced with \( K^+ \) than with \( K^- \). The \( K^+/N_p \) and \( K^-/N_p \) ratios in \( p + Be \) collisions (also shown in figure 6) are smaller than those of central \( Pb + Pb \) collisions. This is in agreement with similar results of other experiments [31]–[33].

The measured effective temperature for the most central \( Pb + Pb \) collisions is \( 126 \pm 5 \) MeV after correcting for protons coming from decays (figure 10). This temperature characterizes the chemical freeze-out of the deuterons and protons, meaning that after that time, deuterons and protons do not change their identity through further collisions. This value is smaller than the temperature of \( \sim 170 \) MeV characterizing the chemical freeze-out of hadrons in full phase space acceptance in central \( S + A \) and \( Pb + Pb \) collisions at 200 and 158 GeV/nucleon.
determined within the framework of thermodynamical models using measured particle yield ratios [34, 35].

The difference in temperature between the value obtained from our analysis using deuteron and proton yields and that using ratios of hadrons (π, K, etc) in other experiments [34, 35], could be due to the limited phase space acceptance of our spectrometer and/or to the fact that deuterons and antideuterons are mainly formed at a later stage of the collision than hadrons. One would expect that nuclei form at the time of thermal freeze-out of hadrons, since they can easily be destroyed in elastic collisions with other particles, due to their weak binding. The thermal freeze-out is the time after which the hadrons no longer interact, through both elastic or inelastic collisions. The temperature of the thermal freeze-out extracted from fits to the \( m_T \) spectral shapes of the hadrons as well as from \( \pi\pi \) interferometry are of the order of \( \sim 120 \) MeV [37]. Consequently, the chemical freeze-out of hadrons occurs at a higher temperature and therefore earlier than the thermal freeze-out. The similarity of the temperature obtained in this study from the \( d/p \) ratios in central \( \text{Pb} + \text{Pb} \) events and the temperature of the thermal freeze-out obtained from spectral shapes and correlations of hadrons, supports the assumption that \( d \) and \( \bar{d} \) are formed mainly at a later stage of the collision than hadrons, namely at the time of the thermal freeze-out of the latter.

The radius of the baryon source extracted from the \( d/p^2 \) ratio increases as \( R \sim N_p^{0.32-0.38} \), and that of the antibaryon source (extracted from the \( \bar{N}/p^2 \) ratio) as \( R \sim N_p^{0.38-0.43} \) (figures 13 and 14), depending on the decay correction applied. In [29] the assumption that freeze-out occurs at a common constant critical density leads to the expectation \( R \sim (N_p)^{1/3} \), assuming that \( N_p \) is proportional to the rapidity density of the charged hadrons at midrapidity. This assumption is supported by the scaling of the \( \pi^- \)-to-\( N_p \) ratio with \( N_p \), observed in heavy-ion collisions [36, 38]. The same dependence holds for radii of nuclei (\( R = 1.2A^{1/3} \) fm). Assuming that the freeze-out occurs when the mean free path of the particles becomes similar to the radius of the particle source, a dependence of \( R \sim (N_p)^{1/2} \) is expected [28]. The \( N_p \) dependence of the source radius extracted in this study from the \( d/p^2 \) yield ratio is in agreement with the expectation \( R \sim (N_p)^{1/3} \). The source radii extracted from the \( \bar{N}/p^2 \) ratio cannot discriminate between the two predictions.

The particle source size in central \( \text{Pb} + \text{Pb} \) collisions at 158 GeV/nucleon has also been deduced from two-particle (e.g. \( \pi\pi \)) correlation analysis [37, 39]. The radii extracted from \( \pi\pi \) interferometry in \( \text{Pb} + \text{Pb} \) collisions at 158 GeV/nucleon, at the same \( y \) and \( p_T \) as the NA52 data and for \( N_p \sim 360 \), are found to be \( R_T \sim 6 \) fm and \( R_L \sim 8 \) fm, where \( R_T \) is the transverse and \( R_L \) the longitudinal radius calculated in the longitudinally comoving system [37]. These radii are not corrected for \( \pi \) yields from resonance decays, however, this correction is predicted to reduce the radius at zero \( p_T \) by less than 10% [40]. Since resonance decays affect the results of the coalescence method \( (R_{\text{COAL}}) \) much more than those of \( \pi\pi \) correlation method \( (R_{\pi\pi}) \), it seems reasonable to compare the decay-corrected \( R_{\text{COAL}} \) to the uncorrected \( R_{\pi\pi} \) values. Furthermore, since the deuteron, nucleon and pion freeze-out mechanisms may differ, the extracted source sizes could be different.

If the particle source was a non-expanding thermal source, the radius extracted from the \( d/p^2 \) ratio would be an estimate of the root mean square radius of the source. However, there is experimental evidence that the particle source in \( \text{Pb} + \text{Pb} \) collisions at 158 GeV/nucleon expands considerably and a collective motion is superimposed on the thermal motion of the particles (e.g. [37, 41]). Therefore, positions and momenta of the particles are correlated and the measured radii are effective values, smaller than the real source dimensions. As a result of the

New Journal of Physics 1 (1999) 22.1–22.23 (http://www.njp.org/)
Figure 15. 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 circles, NA52 experiment) and of those extracted from \( \pi\pi \)-correlations [42] at \( 3.4 < y < 3.9 \) (open stars, NA49 experiment) in \( Pb + Pb \) collisions at 158 GeV/nucleon. Both measurements were performed at similar centrality. The full star shows the radius from \( d/p^2 \) without the correction for the excess of neutrons over protons in the lead nucleus. The displayed curve is a fit of the shown function to the open and full stars. The results of the fit are \( R = (10.4 \pm 0.79)(1 + m_T(9.3 \pm 2.3))^{-1/2} \) fm, with \( \chi^2/DOF = 0.8 \).

Collective source expansion, the effective radius is a decreasing function of the transverse mass \( m_T = \sqrt{p_T^2 + m^2} \) [41].

In figure 15 the results for the source size extracted from \( \pi\pi \) correlations [42] are compared with those obtained from this analysis as a function of \( m_T \). The measurements are performed at a similar rapidity and similar number of participating nucleons. The curve in figure 15 indicates the fit of the function \( R = c(1 + m_T \beta)^{-1/2} \) to the data points shown as stars with \( c \) and \( \beta \) free parameters in the fit. This dependence is expected for a collective expanding source [41]. Our results are seen to be consistent with the \( R_{\pi\pi} \) radii within this picture, after correcting for the \( \Delta \) and \( \Lambda \) decays and without the correction for the neutron/proton asymmetry in lead.
7. Conclusions

Results on the impact parameter dependence of the $K^\pm$, $p$, $d$, $\bar{p}$ and $\bar{d}$ invariant differential yields in $Pb + Pb$ collisions at 158 GeV/nucleon near zero transverse momentum, at rapidities of 3.1 to 4.4 and in the impact parameter range from $\sim$ 2–12 fm have been presented.

The centrality dependence of the antibaryon yields indicates absorption at high baryon density. In the $K^+/N_p$ and $K^-/N_p$ ratios at $y = 4.4$ there is an indication of a threshold behaviour, the ratios rising faster than linear with $N_p$ up to $N_p \sim 80$ and saturating above that value. It is, however, unclear whether this can be related to a QGP phase transition or whether it reflects the onset of thermalization in a hadron gas. The low freeze-out effective temperature of 126 MeV measured in this analysis in the most central events may be related to the late formation of $d$ and $\bar{d}$ through coalescence.

The radius of the particle emitting source extracted from the $d/p^2$ and $\bar{d}/p^2$ ratios is found to be $\sim$ 4 fm for central events near $y_{cm}$, after correcting for decays of $\Delta$ and $\Lambda$. The low value of this radius compared with the source size measured using $\pi\pi$ correlations at similar $y$ and centrality [42] can be understood within a picture of a collective expanding source [41]. The increase of the source radius with $N_p$ is compatible with $R \propto (N_p)^{1/3}$. No sudden change of the chemical potential, the temperature or the radius of the source has been observed.

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