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Deuteron production in central Pb + Pb collisions at 158A GeV

NA49 Collaboration

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Abstract

Experimental results on deuteron emission from central Pb + Pb collisions ($E_{\mathrm{beam}} = 158$A GeV, fixed target), obtained by NA49 at the CERN SPS accelerator, are presented. The transverse mass m_t distribution was measured near mid-rapidity $(2.0 < y < 2.5)$ in the range of $0 < m_t - m_0 < 0.9$ GeV$/c^2$ $(0 < p_t < 2.0$ GeV$/c)$ for the 4% most central collisions. An exponential fit gives an inverse slope $T_d = (450 \pm 30)$ MeV and a yield $dN_d/dy = 0.34 \pm 0.03$. The coalescence factor $B_2(m_t = m_0) = (3.5 \pm 1.0) \cdot 10^{-4}$ GeV^2 and its m_t-dependence are determined and discussed in terms of a model that includes the collective expansion of the source created in a collision. The derived Gaussian size parameter R_G of the emission volume is consistent with earlier HBT results on the source of pion emission.

1. Introduction

Nucleus-nucleus collisions at ultrarelativistic energies offer the unique possibility to study hot and dense nuclear matter (for recent overviews see [1]). Among a variety of species produced in the collisions deuterons form a minor fraction of the emitted particles. The bulk consists of pions with an admixture of kaons and nucleons. This matter forms a hot fireball which cools by expansion. The particles decouple or freeze out from the fireball region at a temperature of $T = 120$–140 MeV [2,3]. Because of their low binding energy of 2.2 MeV deuterons cannot exist within the hot and dense reaction phase; they are only formed very late at freeze-out by nucleons in close proximity and with small relative momenta by means of a coalescence process [4]. Therefore, a measurement of deuteron production allows to study the freeze-out configuration in phase space.

The coalescence picture [5] suggests to relate the phase space density of the emitted deuterons – or, in general, of nuclear clusters with mass number $A = Z_{\mathrm{protons}} + N_{\mathrm{neutrons}}$ – to those of nucleons. This is formulated by the equation

$$E_A \frac{d^3 N_A}{dP_A^3} = B_A \left(E_p \frac{d^3 N_p}{dP_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{dP_n^3} \right)^N , \qquad (1)$$

$$P_p = P_n = P_A / A,$$

where dN is the number of emitted particles, E and P are their energies and momenta. The dependence on the density in configuration space is absorbed into the coalescence factor B_A. Under the assumption of a constant B_A this relation successfully describes the scaling of the yields of light nuclei in nucleus-nucleus collisions at BEVALAC and SIS energies of 0.2–2.0A GeV [6–8] independently of the beam energy and the size of colliding nuclei, as well as in high energy p + p and p + A collisions at FNAL [9]. At the typical AGS energy of 10–15A GeV [10–12] B_A was found to be smaller by an order of magnitude. This was interpreted as evidence that for high energy heavy ion collisions it is also necessary to consider the spatial distribution of the nucleons [3,13]. In such a picture the decrease of B_A with increasing beam

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energy observed in nuclear collisions with large ions can be understood in terms of a collective expansion of the collision zone before break-up [14].

Recently, the coalescence model was refined by Scheibl and Heinz [15]. They employed the similarity of the physics of coalescence and the final state momentum correlations, earlier stressed in [16], extending the investigation to a system with strong collective expansion. Using a hydrodynamically motivated parametrization for the source at freeze-out which implements rapid collective expansion of the collision zone formed in the relativistic heavy ion collisions, they calculated the coalescence probability and invariant momentum spectra for deuterons and antideuterons. To compare the numerical results of the model with experimental data, they used the fireball size and flow parameters obtained from the HBT analysis of two-pion correlations and negative particle spectra measured in the NA49 experiment in central 158A GeV Pb + Pb collisions [2]. The present study of deuteron production in the same experimental conditions provides an important test of the model.

2. Experimental method

The experiment was carried out at the CERN SPS using the NA49 large acceptance hadron detector [17,18]. It mainly consists of four large Time Projection Chambers (TPCs). They provide tracking in the magnetic field and information on the specific energy loss dE/dx in the gas of the TPCs with a resolution of about 4% [17,19].

The tracks of the charged particles emerging from the collision of the ^{208}Pb ion beam with a Pb target of 224 mg/cm^2 in thickness are measured in two Vertex TPCs located in the magnetic field of two superconducting dipole magnets (total bending power 9 Tm) and in two large Main TPCs placed behind the magnet 11 m downstream from the target on either side of the beam axis.

In the present study the particle identification and the separation of the deuterons from the background relies on the particle mass information obtained from two 2.2 m^2 Time-of-Flight (TOF) walls containing 891 pixels each and situated behind the Main TPCs on both sides of the beam. The pixels are scintillator tiles of 60/70/80 mm × 34 mm × 23 mm size viewed by single photomultipliers. The overall time resolution is about 60–70 ps. The particle identification capability in the experiment is shown in Fig. 1a, where the dE/dx value measured in the Main TPC is plotted against the particle mass squared m^2 derived from the TOF information. Whereas deuterons would be completely overshadowed by kaons and protons in the dE/dx projection, they can be cleanly separated on the basis of the TOF information. The acceptance of the TOF system for deuterons (protons) covers the laboratory rapidity range $2.0 < y < 2.5$ $(2.4 < y < 3.0)$ and transverse momenta $p_t < 2.0$ GeV/c.

The central Pb + Pb collisions were selected by a trigger employing the measurement of the forward-

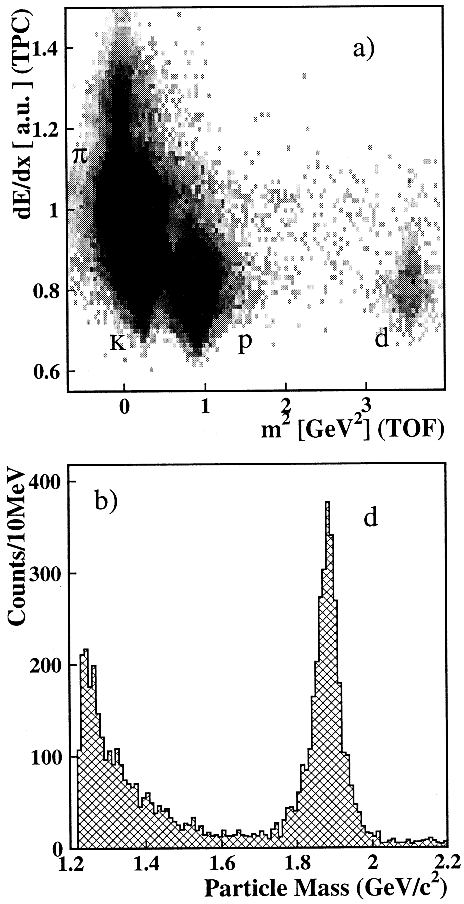

Fig. 1. (a) Particle identification by time-of-flight and dE/dx measurements and (b) Invariant mass distribution after dE/dx cuts in the momentum range $p = 3$–10 GeV/c.

going energy in the Veto Calorimeter, located 27 m downstream of the target. It was set to accept only the 4% most central events of all inelastic Pb + Pb reactions, corresponding to an impact parameter range of $b < 3.5$ fm.

3. Data analysis and results

For the present study 205,000 events were used. In the following, we outline briefly the main steps of the data analysis, in which the information from the TPC and TOF detectors have been used simultaneously. The reconstruction of tracks was performed by a global tracking technique forming track segments in the Main and Vertex TPCs. The reconstructed tracks were extrapolated to the TOF detector plane and were subjected to a number of cuts to reduce the background. Due to the finite granularity of the TOF walls their efficiency for detection of a single particle is less than 100% because of double hits, edge effects as well as conversion pairs created in the scintillator from event-correlated gammas. The sum of all losses, as determined experimentally by comparison with the TPC tracking data, amounts to 25% on average, with a maximum of 32% in the central region closest to the beam. The relevant efficiency corrections have been applied to the data.

The next step of the analysis was the selection of deuterons and the reconstruction of their transverse mass m_t distribution. We defined windows in dE/dx and m^2 which simultaneously maximized the number of deuterons and minimized the background contribution mostly coming from the other particles, i.e. pions, kaons and protons. This selection was performed for (p_t, p) bins of $\Delta p_t = 0.5$ GeV/c and $\Delta p = 1.0$ GeV/c widths in the full kinematical range of deuterons accepted by the TOF detector $0 < p_t < 2.0$ GeV/c and $3.0 < p < 14.0$ GeV/c. The background was negligible over most of the covered phase space reaching about 20% in the region of momenta $p > 12.0$ GeV/c at $p_t > 1.0$ GeV/c. The correction factors for the deuteron loss and background contamination due to the cuts were estimated separately for each (p_t, p) bin. Fig. 1b shows the resulting distribution of the particle mass after dE/dx cuts.

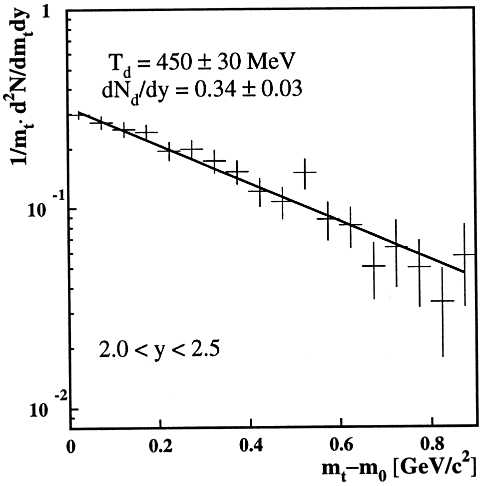

Fig. 2. Transverse mass spectrum for deuterons produced in the 4% most central Pb + Pb collisions at 158A GeV.

Geometrical acceptance and tracking efficiency was obtained from a Monte Carlo simulation of the detector in GEANT. The tracking efficiency was 95% over all the TOF acceptance.

The transverse mass ($m_t = \sqrt{p_t^2 + m_0^2}$, m_0 = particle mass) spectrum for deuterons obtained after all corrections is shown in Fig. 2.

The m_t distribution was fitted with the exponential function:

$$\frac{d^2N}{m_t dm_t dy} = Ce^{-(m_t - m_0)/T}, \quad (2)$$

yielding the following parameters:

$$T_d = 450 \pm 30 \text{ MeV}, \quad dN_d/dy = 0.34 \pm 0.03,$$

where T_d and dN_d/dy are the inverse slope and the deuteron yield respectively. The errors are statistical. dN_d/dy was obtained by integrating the exponential function over the full m_t range. The total errors including systematical ones are estimated to be about 10% for both parameters.

4. Discussion

The transverse mass spectrum of deuterons is observed to be significantly flatter than that of protons. Quantitatively, this is expressed by the inverse slope parameter $T_d \approx 450$ MeV for deuterons compared to $T_p \approx 330$ MeV for protons [24]. Fig. 3 shows the deuteron inverse slope along with those obtained from TOF-identified particles π, K and p near mid-rapidity by fitting the m_t spectra in the range $0 < m_t - m_0 < 1.0$ GeV$/c^2$ for K and p, and $0.3 < m_t - m_0 < 1.0$ GeV$/c^2$ for π respectively. The inverse slopes for ϕ-meson and Ξ-hyperon measured by the NA49 are also presented in Fig. 3. The increase of T with particle mass [20,21] is commonly interpreted as an evidence for a strong collective transverse expansion of the fireball [22].

For deuterons, the shape of the transverse mass spectrum also depends on the coalescence mechanism. A very simple coalescence model assuming an independent source functions in configuration and momentum space predicts the inverse slope of the m_t spectrum of deuterons to be similar to that of protons. However, if the space-momentum correlation is included in the coalescence model the inverse slope of deuterons may deviate from the prediction of the simple coalescence model in the case of strong transverse flow [3,13]. As was shown by Polleri et al. [23] the different slopes of nucleon and deuteron transverse mass spectra require a transverse density profile of the source which is closer to a box than to a Gaussian shape.

In order to obtain the coalescence factor B_2 for deuterons as defined by Eq. (1) the invariant yields

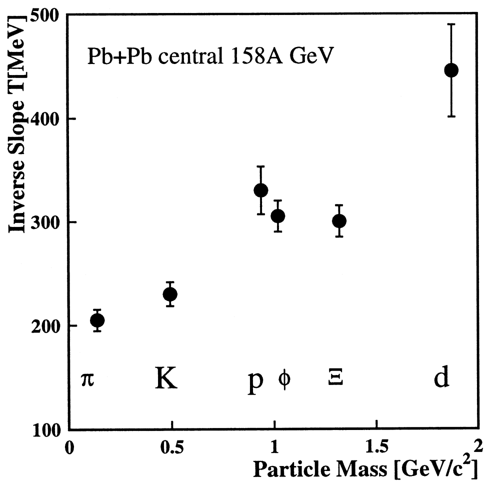

Fig. 3. Inverse slopes for various hadron species near mid-rapidity in central Pb + Pb collisions at 158A GeV.

for nucleons are needed, to be taken at the same rapidity as for deuterons. As usual it is assumed that neutrons behave identically to the protons under our experimental conditions. Data for the latter can be obtained from the NA49 experimental results on net protons, have already been corrected for feed-down from weak decays of Λ and Σ hyperons [24], and revalued for a small fraction of antiprotons ($\bar{p}/p =$ 5–7% as estimated from TOF data). This procedure yields $T_p = 330$ MeV and $dN_p/dy = 32$, with estimated errors of 10% for both quantities.

Eq. (1) applied to the deuteron case reads

$$E_d \frac{d^3N_d}{dP_d^3} = B_2 \left(E_p \frac{d^3N_p}{dP_p^3} \right)^2, \quad P_d = 2P_p, \tag{3}$$

where B_2 [GeV^2] is the coalescence factor for deuterons. Assuming azimuthal isotropy and an exponential m_t-dependence as in Eq. (2) the invariant particle yield at a given rapidity can be written as

$$\begin{aligned} E\frac{d^3N}{dP^3} &= \frac{1}{2\pi}\frac{d^2N}{m_t dm_t dy} \\ &= \frac{1}{2\pi}\frac{dN}{dy}\frac{1}{m_0T+T^2}e^{-(m_t-m_0)/T}. \end{aligned} \tag{4}$$

$B_2(m_t)$ is obtained from (3) and (4):

$$\begin{aligned} &B_2(m_t) \\ &\quad = 2\pi\frac{dN_d/dy}{\left(dN_p/dy\right)^2}\frac{\left(m_pT_p+T_p^2\right)^2}{m_dT_d+T_d^2}e^{-(m_t-m_0)/D}, \end{aligned} \tag{5}$$

where $D = T_p * T_d/(T_p - T_d) = -1.24$ GeV, and m_t is the transverse mass of the deuteron. Inserting the experimental values for the proton and deuteron parameters, we derived for $p_t = 0$

$$B_2(m_t = m_0) = (3.5 \pm 1.0) \cdot 10^{-4} \text{ GeV}^2,$$

with an m_t-dependence determined by the parameter D. This result is displayed in Fig. 4. Above error for B_2 includes both the statistic and systematic errors.

Our result for B_2 is somewhat smaller than the values obtained by other SPS experiments for the same collision system under similar centrality conditions: NA52 [25] reported $B_2 \simeq 6 \cdot 10^{-4}$ GeV^2 (at y

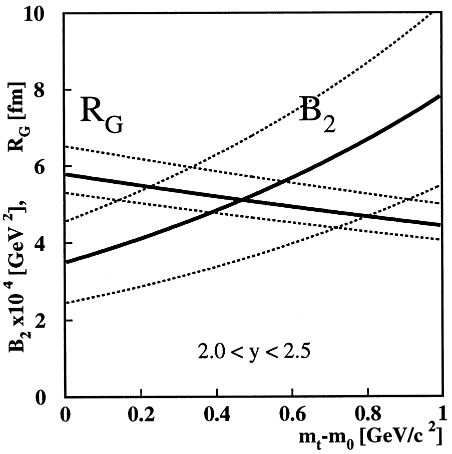

Fig. 4. Coalescence factor B_2 and radius parameter R_G as a function of the deuteron transverse mass for the 4% most central Pb + Pb collisions at 158A GeV (solid lines). The bands indicate the uncertainties (dotted lines).

$=$ 3.75, which is equivalent to $y = 2.1$); NA44 [26] presented $B_2 \simeq 8 \cdot 10^{-4}$ GeV^2 $(1.8 < y < 2.2)$. All three experimental results are in the same range as the value $B_2(m_t = m_0) = (6^{+4}_{-2}) \cdot 10^{-4}$ GeV^2 predicted by the coalescence model [15] mentioned earlier. It should be emphasized that the B_2-values measured at the SPS energy are smaller (by a factor of about 2) than those measured in central Au + Au collisions at the AGS [11,12], while the latter are again smaller by one or two orders of magnitude than the values measured at BEVALAC energies [8]. This can be interpreted as a consequence of the large radial flow and large freeze-out volume reached at higher energies.

In a simplified coalescence model based on the assumption of a static Gaussian nucleon source [27] a relation between the source radius R_G and the B_2-value defined in Eq. (3) can be derived:

$$R_G^3 = \tfrac{3}{4}\left(\sqrt{\pi}\, c\hbar\right)^3 \frac{m_d}{m_p^2}\,\frac{1}{B_2}. \qquad (6)$$

Inserting the measured B_2-values one obtains $R_G(m_t)$ as shown in Fig. 4. R_G becomes m_t-dependent as a consequence of transverse flow. Although the underlying assumptions are only crude approximations, in particular for a source expanding differently in longitudinal and transverse directions, the advantage of this relation is that the resulting ‘‘effective’’ size parameter R_G can be compared directly to pion interferometry results. In Ref. [2] NA49 reported a transverse Gaussian radius $R_G(\mathrm{HBT}) = (6.5 \pm 0.5)$ fm (for transverse velocity $\beta_t = 0$) for the same reaction under identical trigger conditions. The agreement with the deuteron result shown in Fig. 4 ($R_G = (5.8 \pm 0.7)$ fm at $m_t - m_d = 0$) is reasonable. On the other hand, we estimate from our measurement of the two-proton correlation function [28] a smaller effective source radius for proton emission of $3.85 \pm 0.15(\mathrm{stat.})^{+0.60}_{-0.25}(\mathrm{syst.})$ fm.

5. Summary

The transverse mass distribution for deuterons produced in the 4% most central Pb + Pb collisions at 158A GeV in the region $2.0 < y < 2.5$ and $0 < p_t < 2.0$ GeV$/c$ shows an inverse-slope parameter $T_d = (450 \pm 30)$ MeV, which is considerably larger than that of protons. The deuteron yield in this rapidity is measured to be $dN_d/dy = 0.34 \pm 0.03$.

The coalescence scaling factor $B_2(m_t)$ and a Gaussian size parameter $R_G(m_t)$ were derived from comparison to proton invariant m_t spectra. B_2 is found to be at least an order of magnitude smaller than for comparative systems at BEVALAC energies (SPS: 158A GeV, BEVALAC: below 1A GeV). This is consistent with the presence of a strong collective expansion in nucleus-nucleus collisions at SPS energies. The size parameter R_G agrees with the transverse freeze-out radius obtained by pion interferometry for the same collision system.

The values of T_d and B_2 are consistent with the inverse slope and the coalescence probability predicted by a newly developed coalescence model which uses hydrodynamically motivated parameters of the particle emission source and implements rapid collective expansion for central heavy ion collisions.

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