Stopping and Radial Flow in Central $^{58}\text{Ni} + ^{58}\text{Ni}$ Collisions between 1 and 2 AGeV

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Abstract

The production of charged pions, protons and deuterons has been studied in central collisions of $^{58}$Ni on $^{58}$Ni at incident beam energies of 1.06, 1.45 and 1.93 AGeV. The dependence of transverse-momentum and rapidity spectra on the beam energy and on the centrality of the collision is presented. It is shown that the scaling of the mean rapidity shift of protons established for AGS and SPS energies is valid down to 1 AGeV. The degree of nuclear stopping is discussed; the IQMD transport model reproduces the measured proton rapidity spectra for the most central events reasonably well, but does not show any sensitivity between the soft and the hard equation of state (EoS). A radial flow analysis, using the midrapidity transverse-momentum spectra, delivers freeze-out temperatures $T$ and radial flow velocities $\beta_r$ which increase with beam energy up to 2 AGeV; in comparison to existing data of Au on Au over a large range of energies only $\beta_r$ shows a system size dependence.

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One of the main topics of the current relativistic heavy ion experiments is the determination of the properties of nuclear matter at high densities and temperatures \cite{1,2}. Many interesting effects can happen already at densities just twice normal nuclear matter density that can be reached in collisions at incident energies around 1 AGeV: The masses of the constituents can be affected by the surrounding medium due to chiral symmetry restoration \cite{3,4}, a sizable fraction of the constituents can be excited into hadronic resonances whose lifetime and mutual interactions might be different in comparison to the properties of the free particles, and for a short time the system might form an equilibrated state that could give access to the bulk properties of nuclear matter, i.e. to the fundamental nuclear matter equation of state (EoS) \cite{5,7,8}.

Despite many efforts the various effects could not be disentangled so far, although some fascinating observations have been made recently that await a consistent and coherent explanation, e.g. large collective flow \cite{10,11}, low entropy production \cite{12}, reduced pion multiplicities in heavy systems with respect to small systems \cite{13}, and enhanced subthreshold kaon production in central collisions \cite{14}. In order to achieve an understanding of the underlying physics those observations that were obtained at various beam energies and with different systems need to be correlated with each other. This can be done a) by studying different observables in one system under the same conditions, b) by comparing the same observable for a variety of incident energies and system sizes. The latter point is particularly interesting since some observables became available from experiments at the much higher beam energies of the BNL AGS and the CERN SPS, where changes in the development of certain observables could be caused by a possible phase transition to the QCD deconfinement state \cite{15}. Hence a consistent comparison over more than two orders of magnitude in beam energy becomes possible.

A prerequisite for the understanding of the high density and temperature phase of nuclear matter that might have prevailed in the initial stage of the reaction, is the knowledge and
the description of the final state that reflects the properties when the constituents cease to
interact (freeze-out). The freeze-out conditions visible in the distributions of hadrons are
very important since they allow to test concepts like equilibrium and stopping, and therefore
are very useful as a constraint for all more elaborated theories.

This paper presents a rather complete set of data for the phase space distribution (trans-
verse momentum $p_t$ and rapidity $y$) of protons and deuterons as well as pions for the central
collisions of $^{58}$Ni on $^{58}$Ni at incident beam energies between 1 and 2 AGeV, a system for which
pion [16], kaon [17] and $\Delta$ resonance [18] production as well as proton-proton correlations
[19] have already been studied. In the following the centrality and beam energy dependence
of the momentum space distributions of the most abundant hadrons are discussed in detail.
They provide the basic requirements which models need to fulfill, before the discussion of
the initial temperature or baryon density can start. IQMD transport model [20] calculations
are compared to the experimental proton and deuteron rapidity distributions. This allows
to address the question of nuclear stopping power, although in a model-dependent way. We
present the mean rapidity shift of protons and study whether the known scaling behavior
established above 10 AGeV [21] is satisfied at lower beam energies. Finally, we interpret the
midrapidity data in terms of a thermal model including collective radial flow. In order to
facilitate comparison with other data we use the simple assumption proposed by Siemens
and Rasmussen [22], although a lot of effort is devoted to the development and application
of more realistic expansion scenarios [10,23,24].

II. EXPERIMENT

The experiment was performed at the heavy ion synchrotron SIS at GSI by bombarding
$^{58}$Ni beams of 1.06, 1.45 and 1.93 AGeV on a fixed $^{58}$Ni target of 225 mg/cm$^2$ (about 1%
interaction length), placed in the target position of the FOPI detector, which is described
in detail elsewhere [23,24]. For the analysis presented in this paper we used the central
drift chamber (CDC) of FOPI for particle identification, and its forward plastic wall for the
centrality determination. This azimuthally symmetric forward wall covers the polar angles \( \theta_L \) from 7° to 30°, measuring the deposited energy and the time of flight and hence the charge of the fragments. The multiplicity of these fragments, PMUL, was used for the selection of the event centrality. The CDC covers the \( \theta_L \) angles from 30° to 150°. Pions, protons and deuterons were identified in the chamber by means of their mean energy loss \( <dE/dx> \) and their laboratory momentum \( p_L \), obtained from the curvature of the particle tracks in the field of a 0.6 T magnet. The accuracy of the position measurements of the tracks in radial and azimuthal direction via drift time was \( \sigma_{r\phi} \simeq 400\mu m \). The position resolution along the beam direction by charge division was less accurate (\( \sigma_z \simeq 4 \) cm for protons and deuterons and 10 cm for pions). The resolution of the mean energy loss, \( \sigma(<dE/dx)>/<dE/dx> \), was about 15 % for minimum ionizing particles. The resolution of the transverse momentum \( p_t \), \( \sigma(p_t)/p_t \), was about 4 % for \( p_t < 0.5 \) GeV and worsened to 12 % near \( p_t \simeq 2 \) GeV. The phase space covered by the chamber is shown in Fig. 1 for the identified \( \pi^\pm \), protons and deuterons at 1.93 AGeV. Throughout the paper we use the normalized transverse momentum \( p_t^{(0)} \equiv p_t/(\gamma_{cm}\beta_{cm}m_0) \) and the normalized rapidity \( y^{(0)} \equiv y/y_{cm} - 1 \). Here \( y_{cm} \) and \( \beta_{cm} \) are the rapidity and velocity of the center of mass (c.m.), \( \gamma_{cm} = 1/\sqrt{1-\beta_{cm}^2} \), and \( m_0 \) is the rest mass of the considered particles (we use the convention \( \hbar = c = 1 \)).

III. PARTICLE SPECTRA

For a more quantitative investigation we present, in Fig. 2, \( \pi^- \), proton and deuteron spectra in \( \Delta y^{(0)} \) bins of width 0.1. Chosen were two bins at target and at midrapidity for the reaction at 1.93 AGeV, selected by a cut on the upper end of the PMUL distribution representing the most central 100 mb of cross section (the selectivity of such PMUL cuts on the impact parameter is discussed later). The data are plotted in a Boltzmann representation, i.e. \( 1/m_t^2 \cdot d^2N/dm_tdy^{(0)} \) vs. \( m_t - m_0 \), in which a thermalized system is expected to show a single-exponential shape in the absence of flow; \( m_t = \sqrt{p_t^2 + m_0^2} \) and \( m_0 \) are the transverse mass and the rest mass of the considered particle, respectively. As shown by the
dashed lines, the $\pi^-$ spectra can be well described by the sum of two exponential functions, while the proton and deuteron spectra are compatible with one exponential function in our acceptance (with deviations in the range of very low $p_t$ in the target-rapidity bin):

$$\frac{1}{m_t^2} \frac{d^2N}{dm_t dy^{(0)}} = \begin{cases} C_l \cdot e^{-m_t/T_{Bl}} + C_h \cdot e^{-m_t/T_{Bh}} & \text{for } \pi^- \\ C \cdot e^{-m_t/T_B} & \text{for } p \text{ and } d. \end{cases} \quad (1)$$

Here, $C$ is a normalization constant, $T_B$ is the Boltzmann slope parameter, and the subscripts $l$ and $h$ denote the fitting parameters of the $\pi^-$-spectra in the low- and high-$p_t$ range, respectively. The enhancement of pions at low $p_t$ can be understood in terms of the $\Delta(1232)$ resonance decay and in fact can be used to determine the number of $\Delta(1232)$ at freeze-out [18,27]. The enhancement above the single-exponential fit near zero $p_t$ at target rapidity in the proton and deuteron spectra which was already observed at the BEVALAC [28] and at much higher energies at the AGS [29] is attributed to spectator contributions. That is why it is seen only at target rapidity; it disappears as soon as the window is moved by a step of only 0.2 in $y^{(0)}$ towards midrapidity. To obtain the rapidity distributions $dN/dy^{(0)}$, we integrated the fitted functions of Eq. (1) from $p_t = 0$ to $\infty$ in order to account for the missing part in the acceptance (cf. Fig. 1). Both because of these limitations and the fact that we did not try to include the mentioned low-$m_t$ enhancement of protons and deuterons near target rapidity (Fig. 2) the resultant rapidity distributions are expected to represent primarily the distribution of participant matter to which our prime interest is addressed.

In the spectra presented in this paper only the statistical errors are shown. The systematic errors in the $dN/dy^{(0)}$ distributions are different for each particle species and vary with the beam energy and rapidity, the largest values existing for the midrapidity data at 1.93 AGeV, mainly due to the smallest geometrical acceptance. At this energy the integration over the complete $p_t$ range leads to estimated errors of about 2, 5 and 20 % for pions, protons and deuterons at midrapidity, respectively. These values were determined by using three different possibilities, i.e. an exponential shape in Boltzmann and invariant representations and the thermal model including the radial flow (Eq. 4 in Sec. V). The uncertainty in the tracking efficiency (10 %) was obtained by visual inspection of several hundred event dis-
plays and by comparing the results of an analysis with different tracking algorithms [13].

The uncertainty in the particle identification (2 %) was determined by changing the software criteria. Assuming that the sources of these different errors add incoherently, we obtain maximal systematic errors for the $dN/dy^{(0)}$ distributions of 10, 11 and 23 % for pions, protons and deuterons, respectively. A confirmation that the extrapolation procedure over the full $p_t$-range is reasonable is the integrated charge of all reaction products up to $^4$He which for the most central collisions (100 mb) agrees within 10 % with the total charge of the system no matter which spectral form is assumed. The systematic error in $T_B$, caused by the different tracking methods and the different fitting range in $p_t$ is estimated to about 5 %.

A. Centrality Dependence

The centrality dependence was studied in the case of the reaction at 1.93 AGeV. Figs. 3 and 4 show the $T_B$ and $dN/dy^{(0)}$ distributions for different cuts on PMUL thereby varying the selected cross section between the most central 100 mb and 420 mb, representing 4 and 15 % of the total reaction cross section, respectively. The relation between the centrality cuts and the impact parameter $b$ as calculated within the IQMD model are summarized in Table I. Note that the data are measured only for $y^{(0)} < 0$, and then reflected about midrapidity, using the symmetry of the colliding system. It is apparent that the $T_B$ distributions of Fig. 3 are practically identical for the three centrality cuts both for protons and for each of the two pion components, whereas in Fig. 4 a relatively modest enhancement of the midrapidity yield is observed with increasing centrality in the $dN/dy^{(0)}$ distributions of both particles, somewhat more pronounced in case of the pions. When cutting even sharper on centrality we find a saturation of the pion value at about 30 mb, while the proton distribution remains stable below 100 mb. The lack of dramatic changes below an effective sharp-cut impact parameter of about 4 fm indicates a limited impact parameter resolution when using the PMUL selection in a relatively small system such as Ni+Ni.

In the case of global thermal equilibrium one expects the following characteristic rapidity
dependence of the slope parameter $T_B$

$$T_B(y) = T / \cosh(y)$$

leading to a bell-shaped curve for $T_B$ with $T_B = T$ at midrapidity ($y = 0$). This dependence, adjusted to the experimental $T_B$ (125 MeV for protons) at midrapidity, is compared to the experimental results in the lower panel of Fig. 3. It is evident that the data are not described by this global equilibrium assumption, but rather imply that baryonic matter is ‘colder’ away from midrapidity. The failure of the purely thermal scenario is also evident from the experimental proton $dN/dy^{(0)}$ distributions (lower panel Fig. 4): they are much wider than the calculated one for an isotropically emitting thermal source of 125 MeV temperature.

In contrast to the protons we find that the $T_B$ and $dN/dy^{(0)}$ distributions of the high $m_t$ component of the pions are compatible with an apparent global temperature which is however somewhat lower ($T_\pi = 115$ MeV) than implied by the midrapidity value of $T_B$ for the protons (see Figs. 3 and 4). When including the deuteron data (Fig. 3 and 4) into the considerations one notices at midrapidity a pronounced increase of $T_B$ with the mass of the particle.

The fact that the full rapidity distributions of protons indicate incomplete thermalization, while the pion rapidity distributions appear to be ‘thermal’ could indicate any or a combination of both of the following possibilities: only a (midrapidity) fraction of the nucleons are part of a thermally equilibrated fireball that comprises most of the pions or alternatively, there is no fully equilibrated fireball, as suggested by the nucleonic distributions, while the $dN/dy$ distributions of the rather light pions are insensitive to this nonthermal behaviour. Exploring the first possibility, but not definitely excluding the second we shall see later that it is possible to describe the midrapidity $m_t$ spectra of protons, deuterons and pions with a common temperature if one introduces flow (see section V).
B. Beam Energy Dependence

Figs. 5 and 6 show the beam energy dependence of $T_B$ and $dN/dy^{(0)}$ distributions of $\pi^-$, protons and deuterons under a PMUL cut of 100 mb. Generally one finds larger $T_B$ values, especially near midrapidity, when going from 1.06 AGeV to 1.93 AGeV. The high-$p_t$ slope parameter $T_{Bh}$ of the $\pi^-$ spectra changes more than the low-$p_t$ slope parameter $T_{Bl}$ (an increase at midrapidity of 24 % compared to only 11 %). The increase becomes larger for the heavier particles (30 % for protons and 34 % for deuterons), which hints to a larger flow velocity at the higher beam energies. Remarkably there is no significant change of $T_B$ with beam energy near target (projectile) rapidity. In case of the rapidity distributions $dN/dy^{(0)}$ of Fig. 6 we find that the spectra of protons and deuterons exhibit similar shapes at the different energies. This implies that the width of the baryon $dN/dy^{(0)}$ spectra is rather independent of the beam energy, which will be addressed further in the next section. The inverse slope parameters at midrapidity and the integrated particle yields per event are summarized in Table II. For a more thorough discussion of the pion yields and the systematic errors affecting them we refer to [13,16].

IV. BARYON RAPIDITY SPECTRA

Baryon rapidity distributions allow a view on the stopping power of nuclear matter, provided the uncertainties introduced by the limited knowledge of the collision geometry can be controlled. Especially for the present light system, finite particle number fluctuations are important when trying to select head-on collisions. In order to understand the properties of our selection criterion PMUL, we first compare the proton and deuteron $dN/dy^{(0)}$ spectra with the IQMD model [20].
A. Comparison with IQMD

As an example we compare in Fig. 7, the experimental $dN/dy(0)$ distributions of protons and deuterons at 1.93 AGeV for the most central PMUL cut (100 mb) to IQMD model results, obtained with the option of a hard EoS (compression constant $K = 380$ MeV) and a momentum dependent potential, IQMD(HM). The solid lines represent the model results under the same centrality cut as the data, i.e. a PMUL cut on the upper 100 mb in the charged-particle multiplicity spectra for $7^\circ \leq \theta_L \leq 30^\circ$. The dashed lines represent results obtained with the corresponding impact parameter cut. The difference between the solid and dashed lines shows the uncertainty imposed by using PMUL as a centrality criterion instead of the exact $b$. It turns out that the effect is negligible for protons, and small for deuterons. Composite particles from the model were formed by a space coordinate cluster algorithm after an elapsed collision time of 200 fm/c using the standard distance parameter of 3 fm. Under these conditions IQMD underpredicts the deuteron-to-proton ratio by approximately a factor of five. Since we wish to emphasize the shapes of the rapidity distributions all model calculations are normalised to the integral of the data in the figure. We conclude that IQMD reproduces the degree of stopping rather well for the most central collisions. The small 'spectator' shoulder for protons in the model (or the slight peak in the case of the deuterons) is not seen in the data because, as mentioned earlier, the spectator components of the proton and deuteron spectra at low-$p_t$ are suppressed by our integration. The comparison of measured and simulated $dN/dy(0)$ spectra of protons and deuterons in case of the other beam energies shows a similar degree of agreement for the 100 mb cut. Therefore, we conclude that the IQMD model reproduces the shape of the measured proton $dN/dy(0)$ spectra at the most central collisions. IQMD calculations with a soft EoS ($K = 200$ MeV) and momentum dependent potential, IQMD(SM), show very similar results as the IQMD(HM) version, so there is no sensitivity to the stiffness of the EoS in the proton and deuteron rapidity spectra.

Based on these observations, we compare in Fig. 8 the $dN/dy(0)$ model predictions for
protons and deuterons in Ni + Ni collisions (right panel) calculated for zero impact parameter in the IQMD model with results of the isotropic expansion model, using the parameters given in Sec. V (Table IV). Also shown are IQMD predictions for Au + Au collisions of the same energy of 1.06 AGeV (left panel) together with the result of an isotropic expansion scenario using the parameters $T = 81$ MeV and $\beta_r = 0.32$ at 1.0 AGeV from Ref. [11]. In the IQMD model the widths of the $dN/dy^{(0)}$ distributions of protons and deuterons in Au + Au are narrower than in Ni + Ni collisions at the same beam energy. Additionally, the $dN/dy^{(0)}$ for Au + Au collisions can be described nicely by the isotropic expansion model, while the one for Ni + Ni is wider than the model, in accordance with our experimental findings (cf. Fig. 4).

In principle, one can not distinguish incomplete stopping from a longitudinal expansion after full stopping on the basis of the rapidity spectra alone. However, the systematic comparison of the $dN/dy^{(0)}$ spectra between the small and large colliding system within the IQMD model, the results of which are supported by our experimental data in the case of the most central Ni + Ni collisions, can help to resolve this ambiguity. The narrower $dN/dy^{(0)}$ shape of Au + Au as compared to Ni + Ni for $b = 0$ fm indeed tells us that the IQMD model predicts a partial transparency for the latter system. One would expect a wider $dN/dy^{(0)}$ distribution or a smaller mean rapidity shift $\delta y_p$ (as defined in the next chapter) for heavier colliding systems in case of a longitudinal expansion after full stopping. Using the same model, this subject was investigated by Bass et al. by means of the $(n-p)/(n+p)$ ratio in the isospin-asymmetric system $^{50}$Cr + $^{48}$Ca, where a partial transparency was also predicted at an energy of 1 AGeV [30].

B. Scaling of the Mean Rapidity Shift of Protons

Recently, Videbæk and Hansen discussed the systematics of the baryon rapidity losses in central nucleus-nucleus collisions at AGS and SPS energies [21]. The main conclusion was that the mean rapidity losses scaled with the beam rapidity from 10 to 200 AGeV. In
this section we want to study whether this scaling behavior holds at the present lower beam
energies, too, i.e. down to 1 AGeV.

Table III summarizes the results of our analysis and the one of Ref. [21] in terms of the
mean rapidity shift of protons ($\delta y_p$) defined as

$$\delta y_p \equiv \frac{\int_{y_{cm}(\infty)}^{y_{cm}(\infty)} |y - y_t(b)| (dN_p/dy) \, dy}{\int_{y_{cm}(\infty)}^{y_{cm}(\infty)} (dN_p/dy) \, dy},$$

where $y_t$ and $y_b$ represent the target and beam rapidities, respectively, and $dN_p/dy$ is the
proton rapidity distribution. The quantity $\delta y_p$ reflects the inverse width of the rapidity
distribution: The more protons, or baryons in general, pile up at the c.m.-rapidity, the
higher are the $\delta y_p$ values. The scaled shift $\delta y_p/y_b$ is shown in Fig. 9 as a function of beam
energy. For the relatively smaller systems (Ni + Ni at the SIS, Si + Al at the AGS and S + S at the SPS) $\delta y_p/y_b$ is constant for the beam energies between 1 and 200 AGeV, which
implies that the shape of the baryon $dN/dy^{(0)}$ spectra is independent of the beam energies
over this energy range. For the heavier system (Au + Au) both the IQMD prediction at
1 AGeV and the data at 11 AGeV show a slightly larger $\delta y_p/y_b$, which means a higher
concentration of baryons at midrapidity.

V. RADIAL FLOW

There has been a lot of effort to understand the collective motion in heavy ion collisions,
hoping to get a handle on the nuclear equation of state [2]. Especially the radial flow of
the midrapidity fireball as an important energy carrier [10,11,24,31–33] has been studied
extensively. In this section we want to extract the temperature $T$ and the average radial
flow velocity $\beta_r$ from the midrapidity transverse-momentum spectra. We employ the formula
of the simple thermal blast model proposed by Siemens and Rasmussen [22]:

$$\frac{1}{m_t^2 \frac{d^2N}{dmdy^{(0)}}} \propto \cosh y \cdot e^{-\gamma_r E/T} \cdot \left[ (\gamma_r + \frac{T}{E}) \cdot \frac{\sinh \alpha}{\alpha} - \frac{T}{E} \cosh \alpha \right],$$

with $\gamma_r = 1/\sqrt{1 - \beta_r^2}$ and $\alpha = (\gamma_r \cdot \beta_r \cdot p)/T$, where $E = m_t \cosh y$ and $p = \sqrt{p_t^2 + m_t^2 \sinh^2 y}$
are the total energy and momentum of the particle in the c.m. system. In this model, the
thermally equilibrated system expands isotropically, then freezes out suddenly at which time all the particles in the system share a common local $T$ and $\beta_r$.

We are aware that the full event topology is not isotropic and the Ansatz Eq. (4) can therefore at best describe a part of the populated phase space which we restrict to the midrapidity interval $(-0.1 < y^{(0)} < 0.0)$ under the 100 mb PMUL cut. This should minimize the contaminations by spectators and non-isotropic flow components (Fig. 4). The effect of the collective flow can be more significant for heavier particles as seen at lower beam energy [10,33], but at the present energies composite particles are so few that we restrict the analysis to pions, protons and deuterons. For such light particles it was shown in Ref. [11] that details of the flow profile are not discernable because the thermal fluctuations wash them out. This justifies the use of the Siemens-Rasmussen formula which replaces the integration over a complex flow velocity profile by a single 'representative' velocity $\beta_r$. On the other hand, the contamination of the proton and deuteron spectra by products evaporated from the heavier fragments is largely reduced in the energy range we are studying here. Besides simplicity, an important benefit of this simple-minded fit to the data is that a direct comparison with the results of a very similar analysis for the Au + Au system [11] can be done.

Applying the definition of a slope parameter in Eq. 1 to Eq. 4 we evaluate an effective slope $T_B^{\text{eff}}$ from the model as follows

$$T_B^{\text{eff}} \equiv -\left[ \frac{d}{dt} \ln \left( \frac{1}{m_t^2} \frac{d^2N}{dm_t dy^{(0)}} \right) \right]^{-1}. \quad (5)$$

Here $T_B^{\text{eff}}$ shows a combined effect of $T$ and $\beta_r$, and the model gives the estimate of $T_B^{\text{eff}}$ at each $m_t$ value. In the top panel of Fig. 10, our data are shown by bold lines (the fitting errors are smaller than the thickness of each line) together with the model calculations. The $m_t$ range of the fit to the experimental data, which is another important constraint in determining the model parameters, is also indicated. We include only $T_{B,h}$ of $\pi^-$ since the low $p_t$ component of the pion spectra is strongly affected by the $\Delta(1232)$ decay [18,27]. To determine $T$ and $\beta_r$, the two parameters were varied until the model describes our experimental data; the resulting values are summarized in Table IV. The top panel of
Fig. 10 displays the range of the model calculations for $\pi^-$ (horizontally hatched), protons (vertically hatched) and deuterons (diagonally hatched). Having determined $T$ and $\beta_r$, we confirm the results by comparing the spectra from the model with the data directly as shown in the bottom panel of Fig. 10. The results were also checked by the simultaneous fitting method requiring a minimum $\chi^2$ per degree of freedom, and they are consistent with each other within 5%.

Before discussing the results in the framework of general flow systematics it is worthwhile to check on two points:

1) could the fact that resonances other than the $\Delta(1232)$ are excited (but not explicitly treated in the analysis of the high momentum part of the pion spectra) strongly modify the analysis and

2) in view of the fact that the spectral shape analysis requires only (local) thermal equilibrium, can we check that the particle yields are consistent with chemical equilibrium?

We have studied both questions in the context of a hadrochemical equilibrium model [32,33]. The model parameters, chemical freeze-out temperature $T_C$ and baryon chemical potential $\mu_B$, are treated as free parameters, and fixed to reproduce the experimental yields of nucleons, deuterons, thermal pions, $\Delta(1232)$- and $\eta$-mesons from $N^*(1535)$ resonances [33]. The extracted parameters, $T_C$ and $\mu_B$, are also shown in Table IV (for a comparison of the model results with experimental particle yield ratios, see [18]). At all energies the temperature $T$ derived from the spectra including flow agrees with the chemical freeze-out temperature $T_C$ obtained from the particle yields within 8% [34]. The extracted baryon chemical potentials correspond to roughly $0.5 \pm 0.2$ of the saturation density ($0.17 \text{ fm}^{-3}$).

The effects due to higher resonances were estimated using fixed average masses. Within this model, the total freeze-out population of $N^*(1440)$, $N^*(1520)$ and $N^*(1535)$ is estimated to be less than 10% of the $\Delta(1232)$ population at 1.93 AGeV. For freeze-out densities of approximately half the normal nuclear matter density, the contribution of thermal pions compared to the number of pions from resonances with masses larger than the $\Delta(1232)$
resonance exceeds the latter by more than a factor 10. Therefore it is reasonable to assume in the analysis that the high-$p_t$ component of pion spectra is due to the thermal pions.

Fig. 11 shows the comparison of the model parameters $T$ and $\beta_r$ and the fraction of the total available energy per nucleon in c.m. contained in the radial flow motion ($E_{r,\text{flow}}/E_{cm}$, with $E_{r,\text{flow}} = (\gamma_r - 1)m_N$ and $m_N$ being the nucleon mass) from the current analysis with other results for the system Au + Au [10, 11, 33]. Before drawing conclusions from the data presented in Fig. 11 the reader should be aware of the specific differences in the experimental analyses. While the present analysis used midrapidity pion (high $T$ component), proton and deuteron spectra, the EOS collaboration [11] based their conclusions primarily on the 90° (c.m.) spectra of A=2,3 and 4 fragments, but otherwise the same formalism was used as described here. The flow analysis of Ref. [33] was based essentially on a comparison of the mass dependence of the average kinetic energies of Z=1 fragments (i.e. p,d,t). The temperatures were derived in a more indirect way with the help of simulations taking into account evaporation; for the values cited in the figure a freeze-out density of 80% of the ground state density was used which gave the best overall reproduction of the spectral shapes of all the Z=1 and 2 isotopes. Concerning the flow velocities of Ref. [33] we have added a Coulomb correction to the published values. The analysis of [10] extended to fragments with Z=2-8 and to the full measured phase space allowing for a more complex flow profile under the additional constraint of energy conservation.

While some of the straggling in the data points shown in Fig. 11 could well be due to the different methods and data types used to extract the parameters, one can nevertheless discern some general trends. First of all we find that both $T$ and $\beta_r$ increase monotonically as a function of beam energy up to 2 AGeV for both colliding systems. Secondly the temperature $T$ seems to be independent of the system, while the radial flow velocity $\beta_r$ is larger for the larger system size (at least close to 1 AGeV). Intuitively this system size dependence of $\beta_r$ is consistent with our conclusion of the nuclear stopping power in the previous section. The larger nuclei have a larger stopping power, accumulate more pressure in the midrapidity fireball, and as a result the system expands faster. The fact
that the 'freeze-out' temperature turns out to be the same for the Ni as for the Au system does not necessarily mean that the 'primordial' temperature, prior to expansion, was the same. As a matter of fact, within the picture of an adiabatic expansion following maximal compression, one is tempted to conclude that the primordial temperature was somewhat higher in the Au system since the larger collective energy at freeze-out in the heavier system indicates a stronger conversion of thermal energy, hence a stronger cooling. If this tentative interpretation is true, then 'participant' matter in the Ni system, even around midrapidity, has not thermalized as thoroughly as in the Au system at the stage of maximal compression. This shows the necessity to study system size dependences in order to assess quantitatively the degree of equilibration in such collisions.

As a third point we wish to emphasize that the flow energy represents a sizeable fraction of the available energy $E_{cm}$ (lower panel of Fig. 11). In the context of the present work we note that the flow energy in the Ni system (13% of $E_{cm}$ as mean value of the three Ni points) is about half as large as that deduced for the Au system at a comparable energy. From the yields and temperatures (Tables II and IV) we estimate that the baryons take up 50% (at 1.06A GeV), resp. 35% (at 1.93A GeV) of $E_{cm}$ as thermal energy, pion production consumes about 10% (at 1.06A GeV), resp. 17% (at 1.93A GeV). A simple energy balance consideration then leads to the conclusion that a significant fraction (approximately 30 %) of $E_{cm}$ is left in surplus longitudinal movement of the leading baryons for relatively small colliding systems such as Ni + Ni. One should, however, not argue too strongly about the precision of these numbers: the different analysis methods imposing the energy conservation, freeze-out density and flow velocity profiles may favor different sets of $T$ and $\beta_r$.

VI. CONCLUSIONS

We have studied in detail the $\pi^−$, proton and deuteron spectra for central Ni + Ni collisions at beam energies between 1 and 2 AGeV. We do not observe any dependence of the slope parameter of the transverse momentum spectra on the event centrality (from
420 mb to 100 mb), while a higher pion production and a stronger proton concentration at midrapidity is seen for more central events.

The slope parameters are generally larger for higher beam energies, and the effect is more pronounced for the heavier particles; the pion slope parameter for the high transverse-momentum component changes more than the one of the low transverse-momentum component. The rapidity spectra of protons and deuterons show very similar shapes at the different bombarding energies under the same centrality cuts. These shapes are however incompatible with global thermal equilibrium.

The IQMD model can reproduce the measured proton and deuteron rapidity spectra for the most central events, with very similar results for the option of a hard and soft equation of state. The rapidity spectra of protons and deuterons from the IQMD in Au + Au are narrower than in Ni + Ni for vanishing impact parameter, which implies more nuclear stopping power in larger colliding system. The known scaling law for the mean rapidity shift of protons (scaled with the beam rapidity) is satisfied down to 1 AGeV for the small colliding system size.

The freeze-out temperature and radial flow velocity of midrapidity particles increase with the beam energy up to 2 AGeV, but only the radial flow velocity shows a system size dependence. The energy fraction consumed by the radial flow motion is constant for a given colliding system size at beam energies between 0.1 and 2 AGeV. In Ni + Ni collisions this energy fraction is about one half of the value found in Au + Au collisions.

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TABLES

TABLE I. Centrality cuts on the PMUL distributions, related cross sections $\sigma$ and the corresponding impact parameters $b$, calculated with the IQMD model with hard equation of state (EoS) and a momentum dependent potential.

The nuclear radius $R(A)$ is given by $1.2A^{1/3}$, where $A$ is the number of nucleons; the maximum impact parameter $b_{\text{max}}$ is determined by $\sqrt{\frac{\sigma}{\pi}}$.

| System         | $R(A)$(fm) | PMUL | $\sigma$ (mb) | $b_{\text{max}}$(fm) | $<b>_{\text{IQMD}}$(fm) |
|----------------|------------|------|---------------|----------------------|-------------------------|
| $1.93 \text{AGeV Ni + Ni}$ | 4.7        | $\geq 25$ | 420            | 3.7                  | 2.6                     |
|                | $\geq 31$ | 250  | 2.8           | 2.1                  |                         |
|                | $\geq 37$ | 100  | 1.8           | 1.6                  |                         |
| $1.06 \text{AGeV Au + Au}$ | 7.0        | $\geq 76$ | 120            | 2.0                  | 2.8                     |

TABLE II. Inverse slope parameters at midrapidity $T^0_B$ and integrated particle yields per event with a cut on PMUL of 100 mb (cf. Table I). For pions the two slopes with index $l$ and $h$ refer to the low- and high-$p_t$ part of the spectra. Only the dominant systematic errors are quoted. The statistical errors are about 20 and 10 % of the systematic errors of $T^0_B$ and the yields, respectively.

| $E_{\text{beam}}/A$(GeV) | $\pi^-$     | proton     | deuteron    |
|-------------------------|-------------|-------------|-------------|
|                         | $T^0_B/T^0_{Bh}$ (MeV) | Yield       | $T^0_B$ (MeV) | Yield       | $T^0_B$ (MeV) | Yield       |
| 1.06                    | 55±3/93±5   | 3.6±0.4     | 96±5        | 38.4±4.2    | 104±5        | 14.4±2.4    |
| 1.45                    | 56±3/100±5  | 5.8±0.6     | 111±6       | 41.6±4.6    | 120±6        | 12.8±2.6    |
| 1.93                    | 61±3/115±6  | 8.5±0.9     | 125±6       | 44.0±4.8    | 139±7        | 11.6±2.4    |
TABLE III. Summary of the mean rapidity shift of protons (see text for definition). Note that the present analysis includes protons and deuterons. The numbers in parenthesis are the results from the IQMD model calculations with a hard EoS.

| $E_{\text{beam}}/A$(GeV) | $y_b$ | System | $\sigma/\sigma_{\text{tot}}$(%) | $\delta y_p$ | $\delta y_p/y_b$ | Reference |
|--------------------------|------|--------|-----------------|--------|--------|-----------|
| 1.06                     | 1.388 | Ni+Ni  | 3.6             | 0.389  | 0.280  | this work |
|                          |      |        |                 |        |        | (b = 0 fm) |
|                          |      |        |                 | (0.394)| (0.284)| IQMD(HM)  |
| 1.06                     | 1.388 | Au+Au  | $b \leq 0.5$ fm | 0.432  | 0.311  | IQMD(HM)  |
| 1.45                     | 1.586 | Ni+Ni  | 3.6             | 0.453  | 0.285  | this work |
| 1.93                     | 1.782 | Ni+Ni  | 3.6             | 0.503  | 0.282  | this work |
|                          |      |        |                 |        |        | (b = 0 fm) |
|                          |      |        |                 | (0.521)| (0.292)| IQMD(HM)  |
| 11.6                     | 3.21  | Au+Au  | 4.0             | 1.02   | 0.32   | Ref. 21   |
| 14.6                     | 3.44  | Si+Al  | 7.0             | 0.97   | 0.28   | Ref. 21   |
| 200.                     | 6.06  | S+S    | 3.0             | 1.69   | 0.28   | Ref. 21   |

TABLE IV. Summary of radial flow velocities $\beta_r$ and freeze-out temperatures $T$ for the high-$p_t$ part of the pion spectra and of the proton and deuteron distributions in Ni + Ni collisions for the studied energies, derived within the model of Siemens and Rasmussen [22]. The parameters $T_C$ and $\mu_B$ from the chemical equilibrium model [34] are also included.

| $E_{\text{beam}}/A$(GeV) | $\beta_r$   | $T$ (MeV) | $T_C$ (MeV) | $\mu_B$ |
|--------------------------|-------------|-----------|-------------|--------|
| 1.06                     | 0.23 ± 0.03 | 79 ± 10   | 73 ± 10     | 780 ± 30 |
| 1.45                     | 0.29 ± 0.03 | 84 ± 10   | 81 ± 10     | 755 ± 25 |
| 1.93                     | 0.32 ± 0.04 | 92 ± 12   | 90 ± 13     | 725 ± 35 |
FIGURES

FIG. 1. Acceptance of $\pi^\pm$, protons and deuterons at 1.93 AGeV under a centrality cut of 420 mb on PMUL (see text). With the definition of $y(0)$, -1, +1 and 0 denote the target-, projectile- and the c.m.-rapidity. Each successive contour line represents a relative factor of two in terms of yields. The dash-dotted lines show the geometrical limit of the drift chamber at $\theta_L = 30^\circ$, while the dotted line for $\pi^+$ shows the high $p_{Lab}$-cut imposed by the separation against the protons.

FIG. 2. Boltzmann spectra (absolute yield per event) of $\pi^-$ (solid circles), protons (open circles) and deuterons (solid triangles) at target rapidity ($y(0)$ from -1.0 to -0.9, left) and at midrapidity ($y(0)$ from -0.1 to 0.0, right). The data are for 1.93 AGeV collisions with a cut of 100 mb on PMUL. The $\pi^-$ spectra are multiplied by 100 for a clearer display. The dashed lines show the fits with the sum of two exponentials for pions and with one exponential for protons and deuterons.

FIG. 3. Centrality dependence of the Boltzmann slope parameter $T_B$ for $\pi^-$ (separately for the low- and high-$p_t$ component) and protons at 1.93 AGeV. The solid lines are the results of the isotropic expansion model without collective radial flow. For details see Sec. V.

FIG. 4. Centrality dependence of the $dN/dy(0)$ spectra for $\pi^-$ and protons at 1.93 AGeV. The solid lines are the results of the isotropic expansion model without collective radial flow. For details see Sec. V.

FIG. 5. Beam energy dependence of the Boltzmann slope parameter $T_B$ for $\pi^-$ (low- and high-$p_t$ component), protons and deuterons under a cut of 100 mb on PMUL.

FIG. 6. Beam energy dependence of the $dN/dy(0)$ spectra for $\pi^-$, protons and deuterons with a cut of 100 mb on PMUL. For the deuteron data the error bars denote the systematic errors due to the different extrapolations towards $p_t = 0$. 

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FIG. 7. Comparison of experimental proton (left) and deuteron (right) $dN/dy^{(0)}$ spectra (symbols) with results of the IQMD(HM) model at 1.93 AGeV (solid and dashed lines). The solid IQMD curves were obtained under the same cut on PMUL as in the data analysis, the dashed lines under the corresponding impact parameter cut.

FIG. 8. Comparison of $dN/dy^{(0)}$ spectra from the IQMD(HM) model (symbols) with results of the isotropic expansion model (solid lines) for the systems Au + Au (left) and Ni + Ni (right), both at 1.06 AGeV. The IQMD results are for zero impact parameter ($b \leq 0.5$ fm for Au + Au, $b = 0$ for Ni + Ni). The isotropic expansion model uses the parameters given in Table III for Ni + Ni and those of Ref. [11] for Au + Au.

FIG. 9. Mean rapidity shift of protons scaled with the beam rapidity as a function of beam energy. The dashed straight line at 0.28 is only to guide the eye. The data of the AGS and SPS experiments are from Ref. [21].

FIG. 10. Top: $T_B^eff$ vs. $m_t$ of calculations (see text for details) within the isotropic expansion model spanned by the given parameters of $T$ and $\beta_r$ for $\pi^-$ (horizontally hatched), proton (vertically hatched) and deuteron (diagonally hatched) at three beam energies. Bottom: Measured Boltzmann spectra compared to the model calculations (solid lines). Note that the $\pi^-$ spectrum is multiplied by 100 for a clearer display.

FIG. 11. Compilation of results of various experiments, showing $T$, $\beta_r$ and $E_{\text{flow}}/E_{\text{cm}}$, the fraction of available c.m. energy contained in radial flow, as function of the beam energy.
Fig. 1 (Hong et al., PRC)
Fig. 2 (Hong et al., PRC)
Fig. 3 (Hong et al., PRC)

Measured Reflected

\[ T_B (\text{GeV}) \]

\[ T_{Bl} (\text{Low } p_t) \]
\[ T_{Bh} (\text{High } p_t) \]

\[ T = 115 \text{ MeV} \]
\[ T = 125 \text{ MeV} \]

- Proton

\[ y^{(0)} \]
Fig. 4 (Hong et al., PRC)

- Measured
- Reflected
- $\pi^-$
  - $100 \text{ mb}$
  - $250 \text{ mb}$
  - $420 \text{ mb}$

Proton

- $T = 125 \text{ MeV}$
Fig. 5 (Hong et al., PRC)

\[ T_B (\text{GeV}) \]

\[ \pi^- \]

- Measured
- Reflected
- \( T_{Bh}(\text{High } p_t) \)
- \( T_{Bl}(\text{Low } p_t) \)

Proton

Deuteron

\[ y^{(0)} \]
Fig. 6 (Hong et al., PRC)

\[ \frac{dN}{dy}(0) \]

**\( \pi \)**

- **Measured**
  - 1.93 AGeV
  - 1.45 AGeV
  - 1.06 AGeV

**Reflected**

**Proton**

**Deuteron**

\[ y^{(0)} \]
Fig. 7 (Hong et al., PRC)

1.93 AGeV Ni+Ni

- Proton
  - Data, 100mb
  - IQMD (HM)
  - PMUL ≥ 37
  - $b < 1.8$ fm

- Deuteron
  - Data, 100mb
Fig. 8 (Hong et al., PRC)

1.06 AGeV IQMD(HM) and Isotropic Expansion Model

$\frac{dN}{dy^{(0)}}$

Au+Au

Ni+Ni

IQMD (HM), $b = 0$ fm

Isotropic expansion
Fig. 9 (Hong et al., PRC)

\[
\frac{\delta y_p}{y_b} \quad E_{\text{beam}} (\text{GeV})
\]

- SIS
- AGS
- SPS

- Au+Au (Data)
- Ni+Ni (Data)
- Si+Al (Data)
- S+S (Data)
- Au+Au (IQMD(HM), b < 0.5 fm)
- Ni+Ni (IQMD(HM), b=0 fm)
Fig. 10 (Hong et al., PRC)

1.06 AGeV
T = 79(10) MeV
$\beta_r = 0.23(0.03)$

1.45 AGeV
T = 84 (10) MeV
$\beta_r = 0.29 (0.03)$

1.93 AGeV
T = 92(12) MeV
$\beta_r = 0.32 (0.04)$

$T_{\text{eff}}(\text{MeV})$

$T = 79 \text{ MeV}$
$\beta_r = 0.23$

$T = 84 \text{ MeV}$
$\beta_r = 0.29$

$T = 92 \text{ MeV}$
$\beta_r = 0.32$

$(1/m_t^2)(d^2N/dm_t dy(0))/(1/GeV^3)$

$T = 79 \text{ MeV}$
$\beta_r = 0.23$

$T = 84 \text{ MeV}$
$\beta_r = 0.29$

$T = 92 \text{ MeV}$
$\beta_r = 0.32$

$\pi^-$

$\pi^-$ (*100)

$p$

$d$
Fig. 11 (Hong et al., PRC)

![Graph showing temperature (T), average beta (\( \langle \beta_r \rangle \)), and energy flow normalized by center-of-mass energy (\( E_{\text{flow}} / E_{\text{cm}} \)) versus beam energy (E_{beam} in GeV).]

- FOPI Ni+Ni (This Work)
- FOPI Au+Au (Ref. 10)
- FOPI Au+Au (Ref. 33)
- EOS Au+Au (Ref. 11)