NUCLEAR STOPPING POWER IN $\alpha\alpha$ AND dd COLLISIONS


ABSTRACT

Inelastic $\alpha\alpha$ and dd collisions were studied at a centre-of-mass energy $\sqrt{\text{SNN}} = 31.2$ GeV per nucleon–nucleon collision, using the Split-Field Magnet (SFM) detector at the CERN ISR. In this paper we show the inclusive and semi-inclusive rapidity distributions of protons, compare them with predictions of the Lund model, and calculate the average rapidity loss for participant protons. From the negative particles we calculate the inelasticity of the interaction, the average energy per particle, and the degree of isotropy of the produced hadrons.

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1. INTRODUCTION

The momentum or rapidity distributions of protons, measured in hadron-nucleus interactions [1], have been used to estimate the 'stopping power' of nuclear matter for fast nucleons [2]. The nuclear stopping power or nuclear transparency at high energies is a topic of current interest because of two reasons: Firstly, it can be related (in a model-dependent way) to the baryon density achieved during the collision; secondly, it can be related by energy conservation to the energy of produced mesons and, hence (also in a model-dependent way) to the energy density. Baryon and energy density are the two key parameters for the expected phase transition from nuclear matter to a quark-gluon plasma. Whereas there is much theoretical speculation about the nuclear stopping power [3], the experimental data are limited to the quoted data [1], and no information other than from $\alpha\alpha$ collisions ($\sqrt{s_{NN}} = 31.2$ GeV) [4] exists at the moment for high-energy nucleus-nucleus collisions.

In this paper, the momentum distributions of protons and the energy deposited in produced particles are investigated for $\alpha\alpha$ and dd collisions. For comparison also pp data obtained at three different energies ($\sqrt{s} = 30.4, 44.0$, and $62.2$ GeV) are shown. The data were obtained using the Split-Field Magnet (SFM) detector at the CERN Intersecting Storage Rings (ISR). A brief description of the detector and the experimental procedure will be given in Section 2. In Section 3, a recent extension of the Lund model to the case of nucleus-nucleus collisions [5,6] is briefly described, since we use predictions from this model to compare with our experimental results. In Section 4 the inclusive and semi-inclusive rapidity distributions of protons in $\alpha\alpha$ and dd collisions are discussed. Section 5 is devoted to studies of energy deposition during the collisions.

2. EXPERIMENTAL

The SFM detector consists of multiwire proportional chambers laid out to completely enclose the intersection region, and some additional equipment such as time-of-flight (TOF), Cherenkov, and dE/dx counters [7]. It is basically a $4\pi$ magnetic spectrometer, with $\sim 95\%$ acceptance for all inelastic events and with $\sim 80\%$ single-track efficiency. The data presented in this paper were taken using a minimum-bias trigger, which required at least one track candidate in the detector, defined by a coincidence of three or more space points. The events were processed by the standard SFM reconstruction programs. The present analysis is based on $109000$ $\alpha\alpha$ and $106000$ dd inelastic events. The efficiency of the detector and of the reconstruction program was calculated by a Monte Carlo simulation. The measured inclusive distributions were corrected using Monte Carlo generated single-track acceptance tables. For a more detailed description of the experimental procedure, the reader is referred to previous publications [4,8]. Since the largest acceptance losses occur for particles having momenta close to the beam momentum (losses in the beam pipe) one should keep in mind that for positive secondaries with $x_F = 2p_L/\sqrt{s_{NN}} > 1.4$ the spectra have large uncertainties [4].

3. THE LUND MODEL

In the next section we will compare our experimental results with the recently developed extension of the Lund model to the domain of nucleus-nucleus interactions. Thus a brief description of this model is included.

The Lund model provides a phenomenological description of hadronization [5]. Colour charges are assumed to be connected by colour tubes, approximated with relativistic massless strings, the breaking up of which produces the final-state hadrons. In order to generalize the model to hadron-nucleus and nucleus-nucleus interactions this scheme has recently been combined with an independent nucleon model [6]. The projectile and target constituents
(nucleons) are randomly distributed according to Woods-Saxon density distributions (Gaussian for small nuclei) and all binary collisions are recorded, using a frozen straight-line geometry. In each binary collision the two nucleons exchange momentum and, as a result, the nucleons become excited objects (strings) with masses larger than the nucleon mass. When such strings encounter other nucleons their masses gradually increase. After the collision one is left with a set of strings, some of which have collided once and some of which have collided more than once. Each string now undergoes hadronization independent of the others, according to the Lund model for jet fragmentation. The model is able to reproduce a great variety of hadron–hadron, hadron–nucleus, and nucleus–nucleus data [6].

4. BARYON DISTRIBUTIONS

4.1 Proton rapidity distributions

It can be assumed that in inelastic collisions of isoscalar nuclei the inclusive spectra of neutrons are the same as those of protons. Therefore a measurement of the proton spectra contains all information on baryon distributions. As for most detectors, protons cannot be identified in full phase space by the SFM detector, so the proton rapidity distributions cannot be extracted from the data in a direct way. Fortunately, in the case of collisions of isoscalar beams (αα or dd scattering), it is possible to extract the proton rapidity spectra by a statistical method. For both negative and positive secondaries the proton mass is assigned and spectra of negative secondaries are subtracted from those of positive secondaries (dn+/dy − dn−/dy). Since the rapidity spectra for negative and positive pions must be equal, as there is the same amount of u and d quarks in the initial state, their contributions cancel in the difference and as a result one obtains proton rapidity spectra with a correct mass assignment. Note that protons produced in baryon–antibaryon pairs are subtracted as well. The difference in the production of K+ and K− and of heavier fragments (registered with very small efficiency) can be neglected, see Section 4.2.

The result of such a procedure applied to the αα and dd data is shown in Fig. 1 for three different charged particle multiplicity bins. The rapidity distributions are symmetric in the c.m. system, so the results are presented as a function of the absolute value of rapidity |y|. The different multiplicity bins serve as a measure of the impact parameter or ‘centrality’ of the collision. The solid curves correspond to the distributions averaged over all multiplicities. The rather large errors seen in the central rapidity region, |y| < 1, result from taking the difference between two large numbers.

It is seen that the proton rapidity distributions for both αα and dd data are peaked at a value close to the beam rapidity ybeam = 3.51. The visible small shift of the maximum with respect to ybeam, is believed to be due to the quasi-elastic scattering mechanism [9]. With increasing multiplicity the rapidity density increases for |y| < 3, demonstrating that the slowing down of protons is correlated with the centrality of the collision.

4.2 Average rapidity loss

In the following we will estimate the average amount of rapidity ⟨Δy⟩ lost by a participating proton during a collision (Δy = y − ybeam). Obviously, non-interacting spectator protons and quasi-ellastically scattered protons should not be taken into account. We assume that the maximum of the rapidity distribution around |y| = 3.25 is a superposition of two components, namely: a narrow symmetric peak around |y| = 3.25 of spectator protons and a wide distribution approaching zero for |y| = ybeam corresponding to the ‘participant’ protons, which have undergone inelastic collisions. Under this assumption, using a mirror symmetry around |y| = 3.25 for the narrow spectator component, it is possible to subtract this component from the data. At least some part of the diffractively scattered protons will also be subtracted by
this method. The results of the subtraction are shown in Fig. 2, where proton rapidity densities (dn/dy) are plotted against the rapidity loss |Δy|. For both αα and dd data the maxima of the proton distributions move towards larger values of |Δy| as the centrality of the collision increases. Also shown in the figure are the predictions of the Lund model (curves). The calculated spectra correspond to non-pair-produced protons, obtained by subtracting the pair-produced protons (represented by spectra of antiprotons) from the spectra of all protons. The model calculations agree quite well with the data except for small |Δy|. The model was also used to check the influence of the difference of produced positive and negative kaons. In the framework of the model the influence is negligible except in the region Δy < −2.5, where it amounts to around 60% of the excess of positive particles (see dashed curves in Fig. 2).

In order to calculate the average values of rapidity loss ⟨|Δy|⟩, we decided to use the model predictions in the region Δy < −2.5, because of the experimental uncertainties in the data and the possible influence of kaons. Table 1 presents the results for αα and dd data. The quoted errors include possible uncertainties of 20% in the region Δy < −2.5. For both αα and dd data ⟨|Δy|⟩ increases with increasing centrality, but for the corresponding classes of centrality ⟨|Δy|⟩ is the same within errors. We assume here that αα and dd events with the same ratio of charged multiplicity n_{ch} to the average multiplicity ⟨n_{ch}⟩, i.e. fixed n_{ch}/⟨n_{ch}⟩, correspond to approximately the same centrality.

4.3 The multiplicity dependence

In Figs. 3 and 4 the proton yield (dn/dy)dy is plotted as a function of the total charged multiplicity n_{ch} of the event, for different rapidity intervals and for αα and dd collisions, respectively. In the central rapidity interval (|y| < 1) the proton yield is compatible with zero within the present experimental errors for both αα and dd data. In the intermediate rapidity region (1 < |y| < 2) the yield increases linearly with increasing multiplicity in a similar way for αα and dd data. A rather big difference is seen in the rapidity region (2 < |y| < 3) close to the beam rapidity. In the case of the dd collisions, the proton yield flattens out for events with multiplicity larger than 10. In the case of αα interactions, however, the linear rise continues up to larger multiplicities. The behaviour of the proton yield is completely different for the αα and the dd data in the nuclear fragmentation region (3 < |y| < 4). In the dd case the yield decreases linearly with multiplicity, whereas in the αα case it has a maximum around n_{ch} = 20.

Also indicated in the figures are the predictions from the Lund model. The spectator protons are not included in the model; thus no comparison is made for |y| > 3. For the other regions, the agreement is good, except for high multiplicities in the region 2 < |y| < 3.

Qualitatively, the data can be understood as follows. When increasing the multiplicity, events are selected in which an increasing number of nucleons has undergone inelastic collisions or in which the inelasticity of individual nucleon–nucleon collisions increased. Therefore protons are found to be shifted towards smaller rapidities. The differences in the nuclear fragmentation regions (|y| > 3) for αα and dd interactions (Figs. 3d and 4d) can be attributed to the fact that protons from α particles can be bound in heavier fragments (d, t, and 3He; we recall that these fragments are usually lost in the beam pipe); when the multiplicity increases more protons emerge from the beam pipe, since less heavy fragments are produced. It is only for the highest multiplicities in αα interactions, where essentially no heavy fragments are produced, that the proton density at |y| > 3 starts to decrease with increasing multiplicity as a result of the slowing down of the protons [4], as it does for dd interactions right away (since obviously in the latter case no heavy fragments are formed).
5. ENERGY DEPOSITION

5.1 Inelasticity of the collision

For both \( \alpha \alpha \) and dd data, the rapidity of protons decreases with increasing multiplicity (centrality) of the collision. Hence more and more energy is transferred to produce hadrons. As a measure of the amount of deposited energy we use the inelasticity coefficient, \( K = W/\sqrt{s} \); \( W \) is the total energy of the produced hadrons and \( \sqrt{s} = \sqrt{s_{NN}} \) is the total incoming energy in the centre-of-mass system (\( \sqrt{s_{NN}} = 124.8 \) GeV; \( \sqrt{s_{dd}} = 62.4 \) GeV). Since it is impossible to distinguish between produced fast forward moving positive hadrons and scattered protons in our detector, we have chosen \( K_\perp \) as the inelasticity coefficient for this study; \( K_\perp = W_\perp/\sqrt{s} \), where \( W_\perp \) denotes the total energy of the produced negative hadrons. We want to emphasize that \( K_\perp \) is a good measure of the inelasticity of the collision, especially if the number of produced negative, positive, and neutral particles is approximately the same. This is the case for colliding isoscalar nuclei such as \( \alpha \) particles and deuterons. In pp collisions the relation \( W = 3W_\perp \) approximately holds only for the central rapidity region; therefore when comparing \( \alpha \alpha \) and dd with pp data, the cut \( |y| < 2 \) will be used.

We have grouped the events according to the total multiplicity of charged particles. For each group the average multiplicity of negative particles \( n_\perp \) and total average energy \( W_\perp \) carried away by negative hadrons were calculated. Figure 5 shows the inelasticity parameter \( K_\perp \) as a function of \( n_\perp \). The \( \alpha \alpha \) and dd data are compared with pp data at the corresponding energy. In all cases, \( K_\perp \) increases approximately linearly with multiplicity. Assuming that the same amount of energy is carried away by positive and neutral hadrons the total amount of deposited energy, \( 3K_\perp \), reaches 100\% (for dd and pp interactions) and 70\% (for \( \alpha \alpha \) interactions) in the highest multiplicity events.

Averaging over all events, the values \( \langle K_\perp \rangle \) were obtained for negative tracks taken from the full rapidity range and from the range \( |y| < 2 \). These results are presented in Table 2. Since in \( \alpha \alpha \) and dd interactions not all nucleons participate in the collisions, the \( \langle K_\perp \rangle \) values are larger for pp interactions. However, when \( \langle W_\perp \rangle \) for \( |y| < 2 \) (where such a comparison is justified) is normalized to the incoming energy per nucleon–nucleon collision and to the average number of wounded nucleons in the collision \( \langle w \rangle = A_\perp \alpha N/A_\perp \), the numbers of the colliding nuclei and \( \alpha N \) and \( N_A \) are the inelastic nucleon–nucleus and nucleon–nucleus cross-sections, respectively, the corresponding numbers coincide within errors (Table 2, last column). Thus, this observation leads to the conclusion that the amount of energy deposited in a collision is proportional to the average number of wounded nucleons \( \langle w \rangle \) in \( \alpha \alpha \) and dd collisions.

5.2 The average energy of produced hadrons

Figure 6 shows the dependence of the average energy per individual track of produced negative hadrons \( \langle E_\perp \rangle \) on multiplicity for \( \alpha \alpha \), dd, and pp interactions; pp data are shown at three different energies. The \( \langle E_\perp \rangle \) decreases with multiplicity for all data sets, and, as seen in the case of the pp data, it increases with increasing collision energy, at fixed multiplicity. The comparison of \( \alpha \alpha \), dd, and pp data at equal c.m.s. energies \( \sqrt{s_{NN}} = 31 \) GeV shows that, for fixed multiplicity, \( \langle E_\perp \rangle \) is larger in the case of colliding nuclei.

Qualitatively, these data can be understood with the phenomenological picture of multiple independent nucleon–nucleon collisions already employed in Section 4, and taking as input the dependence of \( \langle E_\perp \rangle \) on \( n_\perp \) measured for pp collisions at \( \sqrt{s} = 30.5 \) GeV. Thus for fixed \( n_\perp \), the average energy \( \langle E_\perp \rangle \) must increase with an increasing number of participant nucleons, since the individual collisions must have a multiplicity smaller than the total. (For a more quantitative
understanding one has to account for the known fact that $\langle E_- \rangle$ is smaller than $\langle E_+ \rangle$ in a pp collision, whereas $\langle E_- \rangle = \langle E_+ \rangle$ in a collision of nuclei with isospin = 0; see also Section 4.1).

At the limit of very high multiplicity, several nucleons collide with various degrees of inelasticity. Therefore the average energy $\langle E_- \rangle$ should approach a value equal to the average energy (averaged over all multiplicities) of a hadron produced in a free nucleon–nucleon (pp) interaction. This value is $1.11 \pm 0.08$ GeV for pp interactions at $\sqrt{s} = 30.5$ GeV, which indeed agrees with $\langle E_- \rangle$ measured for $n_- > 10$ in $\alpha\alpha$ and dd collisions.

5.3 Isotropy of hadron production

If in a collision the two nuclei were fully stopped, hadrons would be emitted isotropically from the interaction point. We have therefore studied the correlation between the isotropy of the produced hadrons and the centrality of the collision. As a measure of the isotropy the dispersion of the cosine of the polar angle was chosen ($D = \langle \cos^2 \theta \rangle^{1/2}$). Obviously, $D = 0$ when all particles are emitted perpendicularly to the beam direction and $D = 1$ if the emission is along the beam direction. For isotropic emission, the dispersion should approach the value 0.58. The dispersion has been evaluated for events with different total charged multiplicity. Figure 7 shows $D$ as a function of the reduced multiplicity $n_-/(n)$, already used in Section 4.2. The value of $D$ decreases with increasing multiplicity (centrality) of the collision but stays far away from 0.58. There is no significant difference between the different data samples.

6. SUMMARY AND CONCLUSIONS

The large acceptance of the SFM detector allowed us to measure the spectrum of non-pair-produced protons over a wide rapidity range (corresponding to a range in Feynman $x_F = 2p_T/\sqrt{s_{NN}}$ from 0.1 to 1.4), and integrated over all $p_T$ for $\alpha\alpha$ and dd interactions at $\sqrt{s_{NN}} = 31.2$ GeV. With increasing multiplicity, protons are shifted towards smaller rapidities. Associating higher multiplicity with smaller impact parameter (or more central collisions) we may interpret our observations as an increase of the ‘stopping power’ of nuclear matter with increasing matter thickness. The average slowing down of nucleons amounts to $1.42 \pm 0.04$ and $1.57 \pm 0.08$ units of rapidity for central $\alpha\alpha$ and dd collisions, respectively. For comparison, the rapidity shift is 0.7 units for an average pp collision and is estimated to be 2.4 units for a central $p-$Pb collision [2]. The measured rapidity distribution of protons is in fair agreement with the predictions from the Lund model for nucleus–nucleus interactions.

Basing our investigations on negative particles (dominantly $\pi^-$) we have shown how the inelasticity of the interaction, and the average energy per produced particle as well as its angular distribution varies as a function of multiplicity of produced particles. Whilst we sketched how these data can be qualitatively understood in the framework of a multiple, independent nucleon–nucleon collision model, they will be useful as an input or test for quantitative theoretical calculations.

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Table 1

The average rapidity loss measured for different multiplicity bins in $\alpha\alpha$ and $dd$ collisions

| Multiplicity | $\langle |\Delta y| \rangle$ | Multiplicity | $\langle |\Delta y| \rangle$ |
|--------------|----------------------------|--------------|----------------------------|
| $3 \leq n_{ch} < 7$ | $1.03 \pm 0.05$ | $3 \leq n_{ch} < 5$ | $1.08 \pm 0.09$ |
| $9 \leq n_{ch} < 18$ | $1.26 \pm 0.04$ | $7 \leq n_{ch} < 13$ | $1.25 \pm 0.05$ |
| $25 \leq n_{ch}$ | $1.42 \pm 0.04$ | $18 \leq n_{ch}$ | $1.57 \pm 0.08$ |

Table 2

Values of the average multiplicity $\langle n_- \rangle$, average number of wounded nucleons $\langle w \rangle$, average inelasticity coefficient $\langle K_- \rangle$, and average inelasticity per nucleon–nucleon collision (last column) for $\alpha\alpha$, $dd$ and $pp$ interactions at $\sqrt{s_{NN}} = 31$ GeV

<table>
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<th>Interaction</th>
<th>$\langle n_- \rangle$</th>
<th>$\langle w \rangle$</th>
<th>$\langle K_- \rangle$</th>
<th>$(A/\langle w \rangle) \cdot \langle K_- \rangle$</th>
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<td>$1.7$</td>
<td>$0.076 \pm 0.003$</td>
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<td></td>
<td>$</td>
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<td>$pp$</td>
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<td></td>
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Figure captions

Fig. 1 Proton rapidity distributions for (a) αα and (b) dd collisions at √s_{NN} = 31.2 GeV for three different multiplicity bins. The solid line represents the data averaged over multiplicity.

Fig. 2 Proton rapidity distributions for (a) αα and (b) dd collisions for three different multiplicity bins with the quasi-elastic peak subtracted from the data. The solid and dashed curves represent predictions from the Lund model for nucleus–nucleus interactions for the same multiplicity bins. The solid curves are the predictions for the protons alone (after subtraction of pair-produced protons); the dashed curves include the difference between K^+ and K^- yields (with the wrong, i.e. proton, mass assignment) and thus strictly correspond to the measured difference between positive and negative particles.

Fig. 3 Proton yields per event for different rapidity regions measured in the αα collisions as a function of total charged multiplicity. The solid curves represent the same model calculations as in Fig. 2a.

Fig. 4 Proton yields per event for different rapidity regions measured in the dd collisions as a function of total charged multiplicity. The solid curves represent the same model calculations as in Fig. 2b.

Fig. 5 Dependence of the average inelasticity coefficient K_ on the multiplicity n_ of negatively charged particles (a) for all negative particles in the event, (b) for negative particles only in the range |y| < 2.

Fig. 6 The dependence of the average energy per negative hadron ⟨E_⟩ on the event multiplicity n_.

Fig. 7 Dispersion of the cosine of the polar angle of produced negative hadrons in αα, dd, and pp collisions as a function of the reduced multiplicity.
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Fig. 6
Fig. 7