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A consistent parametrisation for the production rates of negatively charged hadrons and neutral strange particles in nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions

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Abstract

A parametrisation of negative hadron and neutral strange particle production was developed which consistently describes presently available data from nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions at a beam energy of 200 GeV per nucleon. Average multiplicities of negative hadrons are found to be proportional to the number of wounded nucleons, average K_s^0 multiplicities proportional to the number of wounded quarks, and average Λ and $\bar{\Lambda}$ multiplicities proportional to the number of wounded quarks plus an additional contribution proportional to the number of interactions of secondary produced particles. Predictions are given for lead-lead collisions.

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1 Introduction

In recent experiments at the CERN-SPS, beams of light projectiles (proton, oxygen and sulphur) were accelerated up to 200 GeV per projectile nucleon, and collided with nuclear targets [1]. The goal is the observation of exotic states of strongly interacting matter, e.g. the formation of the Quark Gluon Plasma (QGP). Before one can conclude that new effects are a proof of the QGP formation one has to study carefully the consequences of the interaction mechanisms which become possible when nuclei participate in the reaction. For example, the projectile (target) nucleons interact with target (projectile) nucleons in successive collisions (“rescattering”). To be more precise, since the time scale between two NN collisions is too small for hadronization, actually some “intermediate objects” are presumably involved in the further collisions. The second important mechanism which becomes possible in nuclei, is the reinteraction of secondary produced particles inside the nucleus (“cascading”), or final state interactions between produced particles. Since in nucleon-nucleus (NA) collisions both effects (rescattering of the “projectile object” and cascading of the secondary produced particles) are present, NA interactions provide a link between NN and A_1A_2 collisions. In this paper we investigate to what extent enhanced strange particle production in A_1A_2 collisions, which has been proposed as a signature for the QGP [2] and which has been observed in several experiments [1], can be understood in more conventional models.

For such a study it is necessary to build a model which can be simultaneously confronted with the available experimental NN, NA and A_1A_2 data. Unfortunately, a theoretical understanding of the production phenomena, even on the NN level, is still lacking. The reason is that rigorous calculations are impossible in a domain where perturbative QCD does not apply. Effects like rescattering and cascading add more uncertainties to the model predictions. As a result, models based on different dynamical assumptions can give similar results.

As an example we mention the different approaches used in the VENUS model [3] (cascading + double string formation), the RQMD model [4] (cascading + “color rope” formation) and the Dual Parton model (SU(3) symmetric sea for chain formation, $(qq) - (\bar{q}\bar{q})$ production from the sea [5] and string fusion [6]), to describe the multiplicities of K_s^0 , Λ , $\bar{\Lambda}$, and negative hadrons (h^-), observed in central SS collisions by the NA35 collaboration [7]. However, the simultaneous comparison of the model predictions with all available data on negative hadrons and neutral strange particles produced in nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions at an energy of 200 GeV per incident nucleon is still lacking.

The NA35 collaboration has found [8] that the ratios of neutral strange particle to h^- production in selected regions of phase space were the same in OAu and pAu reactions. On the other hand this ratio integrated over the full phase space was measured to be enhanced twofold in SS collisions as compared to pS and NN collisions [7]. The results of the NA36 collaboration [9] show a strong increase of the Λ to h^- ratio for low negative hadron multiplicities in SPb collisions. The dependence levels off at an h^- multiplicity of about 100. While a similar behaviour was observed for $\bar{\Lambda}$, this was

not the case for K_s^0 , where the rise of the K_s^0/h^- ratio with the h^- multiplicity is very weak. A simultaneous comparison of model predictions with all available data (NN, NA, A_1A_2) is clearly needed and will be carried out in this paper for neutral strange particles ($K_s^0, \Lambda, \bar{\Lambda}$) and negative hadrons produced at 200 GeV per incident nucleon.

It will be shown that it is possible to consistently describe the main characteristics of neutral strange particle and negative hadron multiplicities observed in NN, NA and A_1A_2 collisions, using simple parametrizations for their production mechanisms. The yields of K_s^0 and h^- do not seem to be significantly influenced by nuclear effects (like cascading). In contrast, cascading plays an important role for a successful description of the available data on Λ and $\bar{\Lambda}$ production.

2 Parametrization of h^- and K_s^0 production

The assumption that inelastic nucleon-nucleus collisions can be described as an incoherent superposition of the collisions of individual nucleons is an old one. On the basis of the diffractive-excitation model [10], a simple formula for calculating the average multiplicity (mainly pions) $\langle n_x \rangle_{NA}$ in collisions of a high-energy nucleon N with a target nucleus of mass number A was proposed [11]:

$$\begin{aligned} \langle n_x \rangle_{NA} &= \frac{1}{2} \left(\bar{W}^N(A) + 1 \right) \cdot \langle n_x \rangle_{NN} \\ \bar{W}^N(A) &= \bar{W}_1^N(A) \end{aligned} \quad (1)$$

Here, $\langle n_x \rangle_{NN}$ is the average multiplicity of particle species x produced in nucleon-nucleon collisions. $\bar{W}_{A_1}^N(A_2)$ denotes the average number of wounded nucleons in the target nucleus of mass number A_2 , in a collision with a projectile nucleus of mass number A_1 , calculated according to the Glauber model [12]. In eq. (1), as in the other formulae in this chapter, the index denoting the dependence on the impact parameter b is omitted. The formula assumes that the contribution of the incident nucleon to $\langle n_x \rangle_{NA}$ is the same as the contribution of each hit target nucleon and equals approximately $\langle n_x \rangle_{NN}$ ($\bar{W}_A^N(1) = 1$). There is assumed to be no difference whether a nucleon is hit once or several times. The extension of the model to nucleus-nucleus collisions (A_1A_2) is then straightforward [13]:

$$\langle n_x \rangle_{A_1A_2} = \frac{1}{2} \left(\bar{W}_{A_1}^N(A_2) + \bar{W}_{A_2}^N(A_1) \right) \cdot \langle n_x \rangle_{NN}. \quad (2)$$

The consistency of data on negative hadron (mainly pion) multiplicity with the predictions given by eqs. (1) and (2) was shown in [14], for different NA and A_1A_2 collisions at 200 GeV per nucleon. Since the multiplicity in an event is closely related to the number of participating nucleons, and the fluctuations in the number of participants is large compared to the multiplicity fluctuations from a single collision, the produced particle multiplicities are to a large extent dominated by the impact parameter rather than the detailed dynamics, or the structure of the “hadrons” involved in the collisions. These results look surprising when confronted with the observed relative increase of

strange particle production [7–9], and the increase of energy deposited per participating nucleon [15] in nucleus-nucleus collisions.

It was observed [15] that in central SS collisions only a small fraction of the additional energy loss of the incoming nucleons (compared to the NN case) is seen in the pions, either in their number or their average transverse momentum $\langle p_T \rangle$. Instead, this additional energy loss reappears in enhanced strange particle yields, along with equally enhanced baryon-antibaryon production rates. Furthermore, as mentioned in the introduction, it was also found that in the target hemisphere strange particle production in OAu collisions is not enhanced relative to the corresponding pAu data [8]. As pointed out in [16] this could be due to the fact, that each participating target nucleon experiences on average a number of collisions only slightly exceeding unity in OAu and pAu collisions, whereas this number is considerably higher in central SS collisions. These observations suggest first that in contrast to the pion, the strange particle yields depend on the number of collisions suffered by the target and projectile nucleons involved in the collisions, and secondly that strange particles are produced in more energetic collisions. While we have no satisfactory explanations for these observations, we present for motivating the adopted parametrization a simple physical picture, that might help to reconcile the different types of behaviour.

Let us start with a fast-moving nucleon which can be characterized as a system of three valence quarks plus a number of vacuum fluctuations (sea particles) of decreasing momenta, which are sequentially coupled to the valence quark system [17]. At high energies the various quark-gluon configurations in the projectile nucleon are considered to be frozen.

Assuming further that one can describe the scattering of a hadron in a nucleus in terms of these individual components, we may speculate that the momentum transfer in the collision of two nucleons depends on the components which interact. The large configurations of typical hadronic size of 1 fm (mainly from the wee partons) will tend to produce slow hadrons, mainly pions. This could be the reason that pion production is not sensitive to the structure of the colliding “nucleon objects”. In contrast, for the production of strange particles a larger momentum transfer may be needed, and this could require the interactions of the smaller components. We will assume that these components behave like the constituent quarks in the Additive Quark Model (AQM) [18], which allows us to derive a simple expression for calculating the average number of K_s^0 produced in inelastic $A_1 A_2$ collisions:

$$\langle n_{K_s^0} \rangle_{A_1 A_2} = \overline{W}_{A_1}^q(A_2) \cdot \langle n_{K_s^0} \rangle_{NN}. \quad (3)$$

Here $\overline{W}_{A_1}^q(A_2)$ is the mean number of wounded quarks in a projectile nucleus of mass number A_1 , in a collision with a target nucleus of mass number A_2 , calculated according to the AQM. In the model each nucleon in the target and the projectile nucleus can interact one, two or three times, since each constituent quark is assumed to interact only once, giving rise to production of heavier particles. As a consequence, we have a symmetric situation in the number of wounded quarks in the target (A_2) and projectile (A_1) nucleus, $\overline{W}_{A_1}^q(A_2) = \overline{W}_{A_2}^q(A_1)$, even if $A_1 \neq A_2$.

It is interesting to note that according to eqs. (2) and (3) the K_s^0/h^- ratio should

scale as

$$\frac{\langle n_{K_s^0} \rangle_{A_1 A_2}}{\langle n_{h^-} \rangle_{A_1 A_2}} \cdot F_{A_1 A_2} = \frac{\langle n_{K_s^0} \rangle_{NN}}{\langle n_{h^-} \rangle_{NN}}. \quad (4)$$

This “scaling” should be valid for NN, NA and $A_1 A_2$ collisions. The factor $F_{A_1 A_2}$ describes the difference in the production mechanisms of the K_s^0 and h^- . It is equal to the number of wounded nucleons per one wounded quark:

$$F_{A_1 A_2} = \frac{\overline{W}_{A_1}^N(A_2) + \overline{W}_{A_2}^N(A_1)}{2\overline{W}_{A_1}^q(A_2)}. \quad (5)$$

The details of the calculation of the number of wounded quarks $\overline{W}_{A_1}^q(A_2)$ and the number of wounded nucleons $\overline{W}_{A_1}^N(A_2)$ in $A_1 A_2$ collisions are given in Appendix 1.

3 Comparison with the experimental results for h^- and K_s^0 production

In calculating the total yields of negative hadrons h^- and neutral kaons K_s^0 in NA and $A_1 A_2$ collisions, the experimental values for the corresponding yields in NN collisions are used as input values in the eqs. (2) and (3), respectively. In fact, taking into account the difference in the numbers of produced h^- and K_s^0 in nn, np and pp collisions, different “average nucleon-nucleon” multiplicities were used for proton-nucleus ($\langle n_{h^-} \rangle_{NN} = 3.04$, $\langle n_{K_s^0} \rangle_{NN} = 0.19$), and nucleus-nucleus ($\langle n_{h^-} \rangle_{NN} = 3.22$, $\langle n_{K_s^0} \rangle_{NN} = 0.20$) collisions [19].

In Fig. 1a the experimental data on average h^- multiplicities for different (minimum bias) pA collisions (pMg, pAg, pAu [20]; pS [14]; pAr, pXe [21]) at 200 GeV per nucleon, together with the prediction calculated from eq. (2) (full line), are shown. (Note that for $A_1 = 1$ and $A_2 = A$ in eq. (2), eq. (1) is recovered). Good agreement between the data and the model prediction is obtained for all A. The corresponding data for the average K_s^0 multiplicities are shown in Fig. 1b (pMg, pAg, pAu [22]; pAr, pXe [23]; pS [14]). Although the precision of the data prevents a stringent test, we conclude that eq. (3) (for $A_1 = 1$ and $A_2 = A$) is in agreement with the general trend of the data. The above results on average h^- and K_s^0 multiplicities, presented in the form of the K_s^0/h^- ratio, are shown in Fig. 2, as a function of the h^- multiplicity. The model prediction (full line) reflects the A (or h^-) dependence of the quantity F_{1A}^{-1} , i.e. the mean number of wounded quarks per wounded nucleon in pA collisions (see eqs. (4) and (5)). F_{1A}^{-1} is seen to be nearly constant in the A range considered; a slow decrease is predicted due to the saturation of the number of wounded quarks. (For a very big target, $A \gg 1$, the ratio K_s^0/h^- goes to 0, since $\overline{W}_1^q(A)$ goes to 3 and the number of wounded nucleons is proportional to $A^{1/3}$). Therefore, we also expect a stronger rise of the h^- than of the K_s^0 multiplicity, when comparing minimum bias to more central pA collisions. Indeed, such an indication was found in [19] for pAu collisions.

In Fig. 3a results are presented on average h^- multiplicities in nucleus-nucleus interactions at 200 GeV per nucleon, as a function of the total number of participating

(i.e. wounded) nucleons $\overline{W}_{A_1 A_2}^N = \overline{W}_{A_1}^N(A_2) + \overline{W}_{A_2}^N(A_1)$. The data for different nuclear systems as well as for different collision centralities, are taken from the compilation [14], except for the data on h^- production in central SAg collisions ($\overline{W}_{A_1 A_2}^N = 90$) which was taken from [24]. All the data refer to the full phase space. Fig. 3a shows satisfactory agreement between the data and the prediction calculated from eq. (2). The square point in Fig. 3 represents the NN result, used as an input value in the calculation.

On K_s^0 production in full phase space there are only two measurements by the NA35 collaboration in central SS [7] and SAg [25] collisions at 200 GeV per nucleon. In [7] the event selection in SS collisions was varied, according to the number of charged hadrons, in order to obtain event samples with different impact parameters, i.e. different numbers of participating nucleons. Three samples were obtained: peripheral ($\overline{W}_{A_1 A_2}^N = 12 \pm 3$), non-peripheral ($\overline{W}_{A_1 A_2}^N = 42 \pm 6$) and central collisions ($\overline{W}_{A_1 A_2}^N = 54 \pm 6$). The K_s^0 multiplicities in all three samples were measured in restricted regions of phase space. For the central sample, the extrapolation factor f of the measured average K_s^0 multiplicity $\langle n_{K_s^0} \rangle^{\text{acc}}$ to the total 4π multiplicity $\langle n_{K_s^0} \rangle$,

$$\langle n_{K_s^0} \rangle = \langle n_{K_s^0} \rangle^{\text{acc}} \cdot f, \quad (6)$$

could be determined [7]. Assuming that the same extrapolation factor is valid for the peripheral and non-peripheral samples, the results for all three samples extrapolated to full phase space are shown in Fig. 3b together with the data on average K_s^0 multiplicities in NN (square point) and central SAg collisions [25] ($\overline{W}_{A_1 A_2}^N = 90 \pm 10$). The prediction obtained using eq. (2) (full line in Fig. 3b) confirms the conclusion [7, 25] that the K_s^0 yield in central SS and SAg collisions is not proportional to the number of wounded nucleons. However, the predictions obtained by using eq. (3) in which the number of produced K_s^0 is proportional to the number of wounded quarks, describes the data well. The results for SS collisions (dash-dotted curve), SAg collisions (dashed curve) and OAu collisions (dotted curve), are plotted in Fig. 3b versus the number of participating nucleons.

In Fig. 4 the average K_s^0 multiplicity is replotted versus the number $\overline{W}^q$ of wounded quarks. The model prediction eq. (3), shown as the full line in Fig. 4, is a single line for all collision systems in this representation. It is important to emphasize that the model predictions are sensitive to the asymmetry of the nuclear systems involved in the collision. Namely, the model predicts that K_s^0 production tends towards h^- production, as one moves from the symmetric (SS) to the asymmetric (OAu) system. This may explain qualitatively why the ratio of particle multiplicities for K_s^0 and h^- in central OAu and pAu reactions is approximately the same, $R_{K_s^0}(\text{OAu/pAu}) \approx R_{h^-}(\text{OAu/pAu})$, and why the corresponding ratios differ in the case of central SS and pS reactions, $R_{K_s^0}(\text{SS/pS}) > R_{h^-}(\text{SS/pS})$. As shown in Table 1, good quantitative agreement between the model predictions and the data on the multiplicity ratios $R_{K_s^0}$ and R_{h^-} for different nuclear systems (SS/pS, SAg/pS, OAu/pAu) is obtained.

As a further demonstration of the different behaviour of K_s^0 production in symmetric and asymmetric systems, Fig. 5 shows the dependence of the K_s^0/h^- multiplicity ratios on the negative hadron multiplicity for SS (full dots) [7] and SPb (open circles) reactions [9]. The data refer to measurements in restricted regions of phase space. This is taken

into account in the model calculation (curves) by dividing the model results for SS collisions by the extrapolation factor f (see eq. (7)). Since this factor is not derived in [9] for SPb collisions, the model predictions were rescaled to fit the data in the h^- range $80 < h^- < 150$. Again, the different dependence of the K_s^0/h^- ratios on the h^- multiplicity (rise in SS collisions, and approximate constancy in SPb collisions) is well described by the model.

We have shown that two different mechanisms for h^- and K_s^0 production, parametrized by the eqs. (2) and (3) respectively, are required to describe the h^- and K_s^0 multiplicities in nucleon-nucleon and nucleus-nucleus collisions at 200 GeV per nucleon. Fig. 6 summarizes in a synoptic form the agreement of the published data on h^- and K_s^0 production in full phase space with the model predictions using eqs. (2) and (3). The multiplicity ratios K_s^0/h^- multiplied by the mean number of wounded nucleons per wounded quark (eq. (4)) are plotted versus the average negative hadron multiplicity. These ratios from pA collisions (open circles) and A_1A_2 collisions (full dots) are seen to be consistent with the value found for pp collisions (square) and therefore with the basic assumption of the model.

4 Parametrization of Λ and $\bar{\Lambda}$ production

Following the concept of a finite formation length or time, slow particles produced in nuclei (stable particles and resonances) can interact and can be absorbed inside the colliding system giving rise to additional strange particles. Indeed a strong contribution from cascading is observed for positively charged particles in proton-nucleus collisions at backward rapidities [26], indicating that mostly slow baryons reinteract. It was argued by Nikolaev [27] that the production of Λ hyperons in hadron-nucleus interactions (in contrast to K_s^0 production) shows a particularly clear cascading contribution. This was later confirmed by the “microscopic” calculation using the RQMD model [28]. Alternatively, in the VENUS model [3] it is suggested that a significant enhancement of Λ production might be due to production processes which are exclusively present in pA and A_1A_2 collisions, i.e. double string formation. For $\bar{\Lambda}$ production, the models make different assumptions: The RQMD model explains the $\bar{\Lambda}$ enrichment in NA and A_1A_2 collisions mainly due to the “new mechanism” of colour rope formation, while in the VENUS model it is attributed to the interaction of secondary produced particles.

The intention of this paper is not to go into a “microscopic” calculation. Instead it will be shown that in contrast to negative hadron or K_s^0 production, the experimental results on Λ and $\bar{\Lambda}$ production in pA and A_1A_2 collisions cannot be understood by taking into account only the contributions from the primary collisions. For Λ production in pA collisions we will use the parametrization proposed by Nikolaev [27]. $\bar{\Lambda}$ production shows a similar increase relative to h^- production in pA collisions like Λ production, although possibly the production mechanism is different. Nevertheless an analogous parametrization can successfully describe the experimental data. The model will then be extended to nucleus-nucleus (A_1A_2) collisions, without introducing new parameters.

Following [27], the average multiplicity $\langle n_x \rangle_{\text{pA}}$ of particles of type x , produced in pA collisions, is assumed to be a sum of contributions from primary and secondary interactions. To take into account in an approximate way the “leading particle effect” for the “primary” Λ production in pA collisions the proportionality of the average Λ multiplicity to the number of wounded quarks ($\overline{W}_1^q(A)$) is expressed in the form $(\overline{W}_1^q(A) + 1)/2$. With this assumption we can write:

$$\langle n_\Lambda \rangle_{\text{pA}} = \langle n_\Lambda \rangle_{\text{NN}} \cdot \left(\frac{\overline{W}_1^q(A) + 1}{2} + \alpha_\Lambda \cdot \overline{\nu}_K(A) \right), \quad (7)$$

where $\overline{\nu}_K(A)$ is the number of secondary collisions of produced particles. Since the $\overline{\Lambda}$ s (like K_s^0) are mainly produced in the central region, we use the parametrization

$$\langle n_{\overline{\Lambda}} \rangle_{\text{pA}} = \langle n_{\overline{\Lambda}} \rangle_{\text{NN}} \cdot \left(\overline{W}_1^q(A) + \alpha_{\overline{\Lambda}} \cdot \overline{\nu}_K(A) \right). \quad (8)$$

The second terms in eqs. (7) and (8) describe the contributions from secondary interactions. The parameters α_Λ and $\alpha_{\overline{\Lambda}}$ specify, respectively, the numbers of Λ s and $\overline{\Lambda}$ s which are produced per secondary interaction. Since their values are assumed to be independent of A at a given projectile energy, they will be fixed from one pA reaction, namely pAu (see below). Then, from eqs. (7) and (8), we can predict the yields of Λ s and $\overline{\Lambda}$ s for other pA reactions using $\overline{\nu}_K(A)$ calculated from the number of projectile collisions. The number $\overline{\nu}_K$ was determined by the NA5 collaboration [26] in pNe, pAr and pXe collisions at 200 GeV per nucleon projectile energy, as a function of the number n_p of visible protons. A universal dependence of $\overline{\nu}_K(A, n_p)$ on the number of projectile collisions $\overline{W}(A, n_p)$ was observed for all the targets used in the analysis:

$$\overline{\nu}_K(A, n_p) = \overline{W}(A, n_p)^{1.9} - 1. \quad (9)$$

Assuming, according to the NA5 measurements, that eq. (9) is valid for any A the mean number of reinteractions of produced particles can be calculated as a function of A :

$$\overline{\nu}_K(A) = \frac{\sum_{n_p} P_A(n_p) \cdot \overline{\nu}_K(A, n_p)}{\sum_{n_p} P_A(n_p)}. \quad (10)$$

In eq. (10) $P_A(n_p)$ is the probability for producing n_p slow protons in a pA collision. The details of the numerical calculations are presented in Appendix 2. To extend the calculations to nucleus-nucleus collisions, it is assumed that cascading will be fully developed only in the overlap regions of the colliding nuclei, and that these two regions will be sufficiently separated in phase space so that they can contribute independently to the particle production. The amount of cascading in the two overlapping regions, A'_1 and A'_2 , is assumed to be proportional to the incoherent superposition of the contributions from the individual NA' collisions. The numbers of secondary collisions are then given by $A'_1 \cdot \overline{\nu}_K(A'_2)$ and $A'_2 \cdot \overline{\nu}_K(A'_1)$ respectively. Finally, it is assumed that as for K_s^0 the average multiplicities of Λ and $\overline{\Lambda}$ from the primary collisions are proportional to the number of wounded quarks $\overline{W}_{A_1}^q(A_2)$. This implies that both Λ s and $\overline{\Lambda}$ s from primary collisions are produced mainly in the central region. For the Λ hyperons this is questionable, but according to the results obtained by the NA35 collaboration [7]

it appears to be the case in collisions of equal mass nuclei (SS). Despite the fact that for highly asymmetric systems (like OAu) the “leading diquark effect” is important, the same parametrization will be used, which therefore represents an upper limit of Λ production from the primary collisions. With the above assumptions the following expression for the average multiplicity $\langle n_x \rangle_{A_1 A_2}$ ($x = \Lambda, \bar{\Lambda}$) in a collision of two nuclei with atomic number A_1 and A_2 is obtained:

$$\langle n_x \rangle_{A_1 A_2} = \langle n_x \rangle_{NN} \cdot \left[\bar{W}_{A_1}^q(A_2) + \alpha_x \cdot (A'_1 \cdot \bar{\nu}_K(A'_2) + A'_2 \cdot \bar{\nu}_K(A'_1)) \right]. \quad (11)$$

A'_1 and A'_2 denote the numbers of nucleons in the overlapping regions, defined by the impact parameter of the collision.

5 Comparison with the experimental results on Λ and $\bar{\Lambda}$ production

From the experimental data for pAu collisions [22] and nucleon-nucleon collisions [19], one obtains the values for the rescattering parameters in eqs. (7) and (8): $\alpha_\Lambda = 0.19$, $\alpha_{\bar{\Lambda}} = 0.21$. Inserting α_Λ and $\alpha_{\bar{\Lambda}}$ into eqs. (7) and (8) one can predict the average Λ and $\bar{\Lambda}$ multiplicities for other values of A . As shown by the solid curves in Fig. 7, eq. (7) provides a good description of the measured average Λ and $\bar{\Lambda}$ multiplicities in pA collisions [7, 23, 22]. To illustrate the importance of secondary interactions, the prediction (7) without the contribution from secondary interactions ($\bar{\nu}_K(A) = 0$) is shown by the dashed curves, which strongly underestimate the experimental results. In Fig. 8, the Λ/h^- and $\bar{\Lambda}/h^-$ multiplicity ratios are shown as a function of the negative hadron multiplicity together with the model predictions (curves). The Λ/h^- and $\bar{\Lambda}/h^-$ ratios, in contrast to the K_s^0/h^- ratio (see Fig. 2), are systematically higher in pA reactions (dots) than the corresponding ratio obtained for NN interactions (square). In the model, which provides a good description of the data, this rise is due to the second (“cascading”) term in eq. (7).

In Fig. 9a, the data on the average Λ multiplicities from SS [7] and SAg [25] collisions are shown as a function of the number of participating nucleons $\bar{W}_{A_1 A_2}^N$, together with the model predictions (11), given by the solid (SS) and dashed-dotted (SAg) curves. The average Λ multiplicities in full phase space for the peripheral ($\bar{W}_{A_1 A_2}^N = 12$) and non-peripheral ($\bar{W}_{A_1 A_2}^N = 42$) SS samples were calculated using the same extrapolation factor as for central collisions. The prediction (11), when neglecting the contribution from secondary interactions ($\bar{\nu}_K(A) = 0$), is shown by the dashed (SS) and dotted (SAg) curves. Clearly, the model describes the data much better if the contribution from cascading is included. The comparison between the model prediction (with cascading) and the experimental results on the Λ/h^- multiplicity ratios for SS collisions measured by the NA35 [7] (full dots) and the NA36 [9] (open circles) collaborations, is presented in Fig. 10. Again, satisfactory agreement between the model prediction (curve) and the data is obtained. Despite the fact that hadronic rescattering is introduced in the model in a very approximate way, the results suggest the importance

of the secondary interactions between mesons and baryons in creating Λ hyperons in nucleus-nucleus collisions.

As shown above, the average multiplicity of $\bar{\Lambda}$, like that of Λ , increases faster than the average number of wounded quarks in proton-nucleus collisions (see Fig. 7b). Therefore a generic rescattering contribution is required to describe the experimental data. For reasons of simplicity and lack of precise data the rescattering contribution to $\bar{\Lambda}$ production was assumed to be of the same form as for Λ production.

Fig. 9b shows the available results on the average $\bar{\Lambda}$ multiplicities from nucleus-nucleus collisions, together with the model prediction with and without secondary interactions. Again, the model predictions for SS and SAg reactions are in good agreement with the experimental results, when the contribution from cascading is included. The model calculations were performed using eqs. (8) and (11) for pA and A_1A_2 collisions respectively, with $\alpha_{\bar{\Lambda}} = 0.21$ as determined from pAu data [22].

Clearly the similarity of the Λ and $\bar{\Lambda}$ production assumed in the model is in agreement with the available data. However, more diverse and precise experimental results are needed to firm up such a conclusion.

6 Prediction of negative hadron and neutral strange particle production in lead-lead collisions

Very soon measurements of negative hadron and neutral strange particle production will be carried out in lead-lead collisions at the CERN SPS. The predictions of the model calculations for the average multiplicities are shown in Fig. 11, plotted versus the number of participating (wounded) nucleons. The results for h^- and K_s^0 probably represent lower limits since rescattering contributions were assumed to be negligible. Comparing the ratios of average multiplicities plotted in Fig. 12 as a function of the number of participating nucleons, one finds a much slower rise for the ratio $\langle n_{K_s^0} \rangle / \langle n_{h^-} \rangle$ than for $\langle n_{\Lambda} \rangle / \langle n_{h^-} \rangle$ and $\langle n_{\bar{\Lambda}} \rangle / \langle n_{h^-} \rangle$. Moreover the ratio $\langle n_{\Lambda} \rangle / \langle n_{\bar{\Lambda}} \rangle$ is approximately constant as a function of $\langle n_{h^-} \rangle$ whereas the ratio $\langle n_{\Lambda} \rangle / \langle n_{K_s^0} \rangle$ rises significantly. It will be very interesting to see whether the model based on production mechanisms already present in NN and pA collisions can successfully predict particle production in the truly large lead-lead system.

7 Conclusions

A parametrization of negative hadron and neutral strange particle production has been developed which successfully describes presently available data from nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions at 200 GeV per nucleon incident energy.

The parameters of the model were determined from nucleon-nucleon and pAu data. It was found that

- Average negative hadron multiplicities are proportional to the number of wounded

(participating) nucleons in the collision.

- Average K_s^0 multiplicities are proportional to the number of wounded quarks.
- Average Λ and $\bar{\Lambda}$ multiplicities are proportional to the number of wounded quarks plus an additional contribution proportional to the number of secondary rescatterings.

Without new parameters the model reproduces the remaining pA and the available nucleus-nucleus data. Predictions are given for PbPb collisions which will soon be studied at the CERN-SPS.

Appendix 1

The calculation of the number of wounded nucleons and the number of wounded quarks in nuclear collisions

Since certain aspects of the reaction mechanism are much clearer in NA than in A_1A_2 collisions, we will start with the former to demonstrate the main assumptions used in calculating the two quantities $\bar{W}^N$, the number of wounded target nucleons, and $\bar{W}^q$, the number of wounded projectile quarks.

The probability $p_n(b)$ for the projectile to suffer n collisions at a given impact parameter b is given by

$$p_n(b) = \left[\prod_{i=1}^n \sigma_i \right] \exp[-\sigma_{n+1} \cdot T(b)] \int_0^{T(b)} \dots \int_0^{T(b)} d\tau_1 \dots d\tau_n \left[\prod_{i=1}^n \Theta(\tau_{i+1} - \tau_i) \right] \cdot \exp \left[- \sum_{i=1}^n (\sigma_i - \sigma_{i+1}) \cdot \tau_i \right]. \quad (12)$$

Here σ_i ($1 \leq i \leq n+1$) is a sequence of elementary cross sections. If $\varphi(b, z)$ is the two-dimensional density distribution of the target nucleus, the profile function $T(b)$ can be calculated using

$$T(b) = \int_{-\infty}^{\infty} \varphi(b, z) \cdot dz ; \quad \int_{-\infty}^{\infty} d^2\vec{b} \cdot T(b) = A, \quad (13)$$

where $\vec{b} = (b_x, b_y)$ is the impact parameter vector. τ_i and $d\tau_i$ are defined as

$$\begin{aligned} \tau_i &= \int_{-\infty}^{z_i} \varphi(b, z) \cdot dz \\ d\tau_i &= \varphi(b, z_i) \cdot dz_i. \end{aligned} \quad (14)$$

Using eq. (12) one can calculate the mean number of projectile collisions

$$\bar{n}(A) = \frac{\int_0^{\infty} [\sum_{n=1}^{\infty} n \cdot p_n(b)] d^2\vec{b}}{\int_0^{\infty} [\sum_{n=1}^{\infty} p_n(b)] d^2\vec{b}}. \quad (15)$$

The above result depends on the assumption how the sequence σ_i of elementary cross sections changes with the number of collisions of the “projectile”.

To see that, let us start with the assumption that the cross section of the “projectile object” is σ_{NN} , independent of the number of its collisions. In this case, since $\sigma_i = \sigma_{NN}$ ($1 \leq i \leq n+1$), and consequently $\sigma_i - \sigma_{i+1} = 0$, eq. (12) simplifies considerably and we get the well known Glauber result [12]

$$p_n(b) = \frac{(\sigma_{NN} \cdot T(b))^n}{n!} e^{-\sigma_{NN} \cdot T(b)}. \quad (16)$$

Inserting (16) into eq. (15) we obtain the result for the mean number of wounded nucleons (see eq. (1)) ($\bar{W}_1^N(A) = \bar{n}(A)$):

$$\bar{W}_1^N(A) = \frac{A \cdot \sigma_{NN}}{\sigma_{NA}}, \quad (17)$$

where σ_{NA} is the inelastic cross section given by

$$\sigma_{NA} = \int_0^\infty \left[\sum_n p_n(b) \right] d^2\vec{b} = \int_0^\infty (1 - e^{-\sigma_{NN} \cdot T(b)}) d^2\vec{b}. \quad (18)$$

Now we will calculate (15), assuming that $\sigma_1 = \sigma_{NN}$, $\sigma_2 = \frac{2}{3}\sigma_{NN}$, $\sigma_3 = \frac{1}{3}\sigma_{NN}$ and $\sigma_{i>3} = 0$. Under these assumptions eq. (15) can be written in the form

$$\bar{W}^q(A) = \frac{1}{\sigma_{NA}} \cdot \int_0^\infty d^2\vec{b} \cdot \sum_{n=1}^3 \binom{N_c}{n} \cdot (1 - e^{-\sigma_{qN} T(b)})^n \cdot e^{-(N_c - n) \cdot \sigma_{qN} \cdot T(b)}. \quad (19)$$

Here N_c denotes the number of constituent quarks in a projectile ($N_c = 3$ for proton, neutron), and σ_{qN} is the inelastic quark-nucleon cross section, $\sigma_{qN} = \frac{1}{3}\sigma_{NN}$. This result, obtained a long time ago in ref. [18], was interpreted in the frame of the AQM as the mean number of interacting projectile quarks in NA collisions.

For practical reasons, we will calculate the mean number of wounded nucleons and quarks in NA and $A_1 A_2$ collisions using a Monte Carlo simulation. The computer code is flexible enough to allow a change of the elementary cross section σ_{NN} with the number of collisions, and it provides the possibility to obtain results for different impact parameter selections in an easy way.

The first step in the Monte Carlo simulation calculates the coordinates x_j, y_j, z_j ($j = 1, \dots, A$) of the target nucleons, according to a nuclear density distribution $\rho(r)$,

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - r_0)/a]}. \quad (20)$$

The parameters $r_0(A)$ and $a(A)$ are taken from the Fritiof model [29].

In calculating the number of wounded nucleons in NA collisions, the projectile nucleon is assumed to move on a straight line, defined by the impact parameter b , through the nucleus, making an interaction whenever it comes close enough to a target nucleon N_j :

$$(x_0^p - x_j)^2 + (y_0^p - y_j)^2 \leq \frac{\sigma_{NN}}{\pi} \quad (21)$$

$$j = 1, \dots, A; \quad x_0^p = b_x; \quad y_0^p = b_y.$$

Here the coordinates of the projectile nucleon x_0^p, y_0^p are taken to be the x and y components of the impact parameter vector $\vec{b} = (b_x, b_y)$, defined in the center of mass of the target system.

The extrapolation to nucleus-nucleus ($A_1 A_2$) collisions is obvious. The number of projectile and target nucleons (with the coordinates $x_i^p = x_i + b_x, y_i^p = y_i + b_y$ ($i = 1, \dots, A_1$) and x_j, y_j ($j = 1, \dots, A_2$) respectively) which will participate in the collisions can be calculated, demanding that

$$(x_i^p - x_j)^2 + (y_i^p - y_j)^2 \leq \frac{\sigma_{NN}}{\pi} \quad (22)$$

$$i = 1, \dots, A_1; \quad j = 1, \dots, A_2.$$

A similar procedure is used to calculate the number of wounded quarks, according to the AQM, except that the changes of the cross section after the first, second and third collision are taken into account. Thus, in nucleon-nucleus collisions the “projectile object” N^* will interact with a target nucleon if

$$(x_0^p - x_j)^2 + (y_0^p - y_j)^2 \leq \frac{\sigma_k^*}{\pi}$$

$$\sigma_k^* = \begin{cases} \sigma_{NN} \cdot \frac{(N_c + 1 - k)}{3} & k = 1, 2, 3 \\ 0 & k > 3. \end{cases} \quad (23)$$

Here σ_k^* denotes the N^*N cross section for the first, second and third ($k = 1, 2, 3$) collision of the N^* with the target nucleons. For nucleus-nucleus ($A_1 A_2$) collisions the situation is more complicated, since we have to take into account the fact that the cross section is changing, depending on how many collisions the target and the projectile nucleons have undergone before. In this case, one projectile nucleon with the coordinates x_i^p, y_i^p, z_i^p , having had k_p^i ($= 0, 1, 2$) collisions, will interact with the target nucleon (x_j, y_j, z_j) having had k_t^j ($= 0, 1, 2$) collisions if

$$(x_i^p - x_j)^2 + (y_j^p - y_j)^2 < \frac{(N_c - k_p^i)}{3} \cdot \frac{(N_c - k_t^j)}{3} \cdot \frac{\sigma_{NN}}{\pi}. \quad (24)$$

If k_p^i (k_t^j) is greater than 2, the wounded projectile (target) nucleon is not allowed to interact, as postulated in the AQM model.

Fig. 13 shows the number of wounded target nucleons $\bar{W}_1^N(A)$ (full curve) and the number of wounded projectile quarks $\bar{W}_1^q(A)$ (dashed curve) for minimum bias NA collisions, as a function of the target mass number A . The Monte Carlo results presented in Fig. 13 reproduce the results obtained using eqs. (17) and (19). Note that for NA collisions $(\bar{W}_1^N(A) + 1)/2 \approx \bar{W}_1^q(A)$. As an illustration of the impact parameter dependence in the case of $A_1 A_2$ collisions, Fig. 14 shows the average number of wounded quarks $\bar{W}_A^q(A)$ as a function of the average number of wounded nucleons $\bar{W}_A^N(A)$ in SS collisions.

Appendix 2

Here we will show the procedure used to calculate the probability $P_A(n_p)$ for producing n_p slow protons in a pA collision, which enters into the eq. (10). $P_A(n_p)$ is obtained from the formula

$$P_A(n_p) = \frac{\sum_n \Pi_A(n) \cdot P_A^n(n_p)}{\sum_n \Pi_A(n)} \quad (25)$$

proposed in ref. [30]. The probability $\Pi_A(n)$ that a projectile collides n times inside the nucleus of mass number A , was calculated from

$$\Pi_A(n) = \frac{1}{\sigma_{NA}} \cdot \int d^2\vec{b} \cdot p_n(b), \quad (26)$$

where σ_{NA} and $p_n(b)$ are given by eqs. (18) and (16) respectively. The probability distribution $P_A^n(n_p)$ of the number n_p of slow protons for n collisions of the projectile inside the nucleus of mass number A , was given in ref. [30]:

$$P_A^n(n_p) = \binom{n_p - n - 1}{n_p} \cdot (1 - x)^n \cdot x^{n_p} \quad (27)$$

where

$$x = (\langle n_p \rangle_A / \overline{W}(A)) / (1 + \langle n_p \rangle_A / \overline{W}(A)) \quad (28)$$

and $\langle n_p \rangle_A / \overline{W}(A)$ is the average number of knocked out protons in one projectile collision. One can define the moments of the distribution of the number of projectile collisions $\Pi_A(n)$

$$\langle W(A)^q \rangle = \overline{W}(A)^q = \frac{\sum_n n^q \cdot \Pi_A(n)}{\sum_n \Pi_A(n)}. \quad (29)$$

The mean number of projectile collisions $\overline{W}(A)$ is, of course, obtained with $q = 1$. The mean number of slow protons $\langle n_p \rangle_A$ is computed from the formula

$$\langle n_p \rangle_A = 0.5 \left(\frac{Z}{A} \right) \cdot \langle W(A)^2 \rangle \quad (30)$$

proposed in ref. [31] and is proportional to the second moment ($q = 2$ in eq. (29)). With the results from eqs. (26-30) one can calculate the probability $P_A(n_p)$ defined by eq. (25). For calculating the number of rescatterings $\overline{\nu}_K$ in eqs. (9) and (10) one still needs to calculate $\overline{W}(A, n_p)$, the mean number of projectile collisions in interactions leading to n_p slow protons, which can be written as:

$$\overline{W}(A, n_p) = \frac{\sum_n n \cdot \Pi_A(n) \cdot P_A^n(n_p)}{\sum_n \Pi_A(n) \cdot P_A^n(n_p)}. \quad (31)$$

Formula (31) can be evaluated by inserting the results from eqs. (27) and (28). In Fig. 13 the dotted curve shows the final result, i.e. the number of secondary intranuclear interactions $\overline{\nu}_K(A)$ as a function of the mass number A .

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Table 1: Ratios R_x of average multiplicities of particle species x for various A_1A_2 and pA collisions. Model predictions are given in parentheses.

	SAg/pS	SS/pS	OAu/pAu
R_π	32 ± 2 (30.6)	19 ± 1 (18.7)	$16 \pm 1^{**}$ (15.8)
$R_{K_s^0}$	47 ± 6 (47.9)	38 ± 8 $35 \pm 4^*$ (30.9)	$15 \pm 3^{**}$ (21.3)

* $K_s^0 = (K^+ + K^-)/2$ for SS

** data only in the backward region

Figure Captions

- Fig. 1: Average multiplicities $\langle n_{h-} \rangle$ of negative hadrons (a) and $\langle n_{K_s^0} \rangle$ of K_s^0 (b), produced in NN (squares) and pA (dots) collisions at 200 GeV, versus the target mass number A . The curve shows the model prediction eq. (1) in (a) and eq. (3) in (b).
- Fig. 2: Ratio of average multiplicities $\langle n_{K_s^0} \rangle$ of K_s^0 and $\langle n_{h-} \rangle$ of negative hadrons versus the average h^- multiplicity in NN (square) and pA (dots) collisions at 200 GeV. The model prediction is shown by the curve.
- Fig. 3: Average multiplicities $\langle n_{h-} \rangle$ of negative hadrons (a) and $\langle n_{K_s^0} \rangle$ of K_s^0 (b), produced in NN (squares) and $A_1 A_2$ (dots) collisions at 200 GeV per nucleon, versus the total number of nucleons $\bar{W}_{A_1 A_2}^N$ participating in the collision. The predictions of eq. (2) are shown by the solid curves in (a) and (b), predictions of eq. (3) are shown in (b) for SS (dash-dotted), SAg (dashed) and OAu (dotted) collisions.
- Fig. 4: Average multiplicity $\langle n_{K_s^0} \rangle$ of K_s^0 versus the number of wounded quarks $\bar{W}_{A_1}^q(A_2)$ for NN (square) and various $A_1 A_2$ (dots) collisions at 200 GeV per nucleon. The line represents the model prediction eq. (3).
- Fig. 5: Ratio of average multiplicities $\langle n_{K_s^0} \rangle$ of K_s^0 and $\langle n_{h-} \rangle$ of negative hadrons, produced in NN (square, ref. [19]), SS (dots, ref. [7]) and SPb (open circles, ref. [9]) collisions at 200 GeV per nucleon, versus the average negative hadron multiplicity $\langle n_{h-} \rangle$. The curves show the model predictions.
- Fig. 6: Ratio of average multiplicities $\langle n_{K_s^0} \rangle$ of K_s^0 and $\langle n_{h-} \rangle$ of negative hadrons scaled by F , the mean number of wounded nucleons per wounded quark (see eq. (4)), versus the average number of negative hadrons $\langle n_{h-} \rangle$ in NN (square), pA (open circles) and $A_1 A_2$ (dots) collisions at 200 GeV per nucleon.
- Fig. 7: Average multiplicities $\langle n_\Lambda \rangle$ of Λ (a) and $\langle n_{\bar{\Lambda}} \rangle$ of $\bar{\Lambda}$ (b) hyperons, produced in NN (square) and pA (dots) collisions at 200 GeV, versus the target mass number A . The full (dashed) curve shows the model prediction eq. (7) including (excluding) the cascading contribution.
- Fig. 8: Ratio of average multiplicities $\langle n_\Lambda \rangle / \langle n_{h-} \rangle$ of Λ (a) and $\bar{\Lambda}$ (b) hyperons to negative hadrons, produced in NN (square) and pA (dots) collisions at 200 GeV, versus the average number $\langle n_{h-} \rangle$ of negative hadrons. The curve shows the model prediction.
- Fig. 9: Average multiplicities $\langle n_\Lambda \rangle$ of Λ (a) and $\langle n_{\bar{\Lambda}} \rangle$ of $\bar{\Lambda}$ hyperons (b) versus the total number of participating nucleons $\bar{W}_{A_1 A_2}^N$ in NN (square, ref. [19]), SS (dots, ref. [7]) and SAg (open circles, ref. [25]) collisions at 200 GeV per nucleon. The solid (dashed-dotted) curves show the model predictions for SS (SAg) collisions including the cascading contribution. The dashed (dotted) curves show the model results for SS (SAg) collisions excluding cascading.

- Fig. 10: Ratio of average multiplicities $\langle n_\Lambda \rangle$ of Λ hyperons and $\langle n_{h^-} \rangle$ of h^- , produced in NN (square, ref. [19]) and SS (dots, ref. [7]; open circles, ref. [9]) collisions at 200 GeV per nucleon, versus the average h^- multiplicity $\langle n_{h^-} \rangle$. The curve shows the model prediction for SS collisions.
- Fig. 11: Model predictions for the average multiplicities of (a) negative hadrons, (b) K_s^0 mesons, (c) Λ hyperons, (d) $\bar{\Lambda}$ hyperons in PbPb collisions at 200 GeV per nucleon versus the number of participating nucleons $\bar{W}_{A_1}^N(A_2)$.
- Fig. 12: Model predictions for the ratios of average multiplicities $\langle n_{K_s^0} \rangle / \langle n_{h^-} \rangle$ (full), $\langle n_\Lambda \rangle / \langle n_{h^-} \rangle$ (dashed) and $\langle n_{\bar{\Lambda}} \rangle / \langle n_{h^-} \rangle$ (dotted) of K_s^0 , Λ and $\bar{\Lambda}$ to negative hadrons in PbPb collisions at 200 GeV per nucleon versus the number of participating nucleons $\bar{W}_{A_1}^N(A_2)$.
- Fig. 13: Calculated average number of wounded target nucleons $\bar{W}_1^N(A)$ (full), wounded projectile quarks $\bar{W}_1^q(A)$ (dashed), and rescatterings $\nu_K(A)$ (dotted) in a collision of a nucleon with a nucleus of mass number A at 200 GeV.
- Fig.14: The average number of wounded quarks $\bar{W}_A^q(A)$ versus the average number of wounded nucleons $\bar{W}_A^N(A)$ in SS collisions at 200 GeV per nucleon, calculated for different impact parameters.

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Fig. 12

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