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FLAVOR FLOW IN ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS: THE RQMD APPROACH

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1 Introduction

One of the central goals of today's nuclear physics is the search for exotic states of strongly interacting matter (e. g. the formation of a quark-gluon plasma). High energetic collisions between two nuclei are the only tool to probe nuclear and quark matter far beyond the nuclear ground state, at densities several times the densities found in the interior of nuclei and at temperatures which were only realized in the universe shortly after the big bang (around 200 MeV). At the high energy laboratories CERN and BNL proton, oxygen and sulphur (CERN-SPS), respectively silicon (BNL-AGS) ions have been accelerated and collided with different targets. The maximum beam energies have been 200 AGeV (at CERN) and 14.5 AGeV (at BNL). Now experiments with truly heavy ion projectiles have just started (with a gold beam at BNL) or are under way (Pb(160 AGeV) + Pb at CERN).

The ultimate challenge for experimentalists and theorists is the extraction of the equation of state and in particular the phase diagram from the experimental observations in nucleus-nucleus collisions. However, the relationship between experimental data and bulk properties of strongly interacting matter is far from being simple. The reaction starts from an extreme nonequilibrium situation, two baryon currents

pointing into opposite directions. Whatever the time scale is before the system gets thermalized (if ever), it is obvious that there will be a stage in every nuclear collision to be characterized by some sort of nonequilibrium dynamics. The system which is created in nuclear collisions has a lifetime on the order of up to 10 fm/c in its extremely hot and dense stage. Its volume is approximately given by the extension of the overlap region of the two colliding nuclei. So finite size effects will always be important for an analysis which tries to relate experimental data to "infinite matter" properties. The understanding becomes even more difficult, because the hadrons which are experimentally detected form only the "ashes" of the initially hot fireball. Comparable to using archeological methods one has to trace back from the final state the earlier reaction stages which are more interesting than the final hadronic "freeze-out". By definition the freeze-out of the hadrons can only occur if they are forming already a rather dilute gas. Particles which are interacting only electromagnetically with the medium (photons, leptons) may escape earlier, because their mean free path is large compared to the size of the interaction region. However, it is not clear from the beginning whether electromagnetic signals from the early reaction stages are not buried under the particles sent out later on. All these uncertainties in relating the finally observed particles to the transient stage of the nuclear reactions in which the system is highly excited and compressed call for detailed models which try to follow theoretically the path of the nuclear reaction dynamics.

2 The RQMD approach

In the following we will describe the main features of relativistic quantum molecular dynamics (RQMD). RQMD is a microscopic phase space approach and generates complete events which can be directly compared to experimental data. In the first stage of a nuclear collision projectile and target nucleus are interpenetrating each other. Resonances or strings are excited when two nucleons or later on constituent quarks collide with interaction probabilities given by geometry. If the minimum two body CMS distance is below $\sqrt{\sigma/\pi}$ with σ either the free nucleon-nucleon cross section or a (di-)quark nucleon/quark cross section ($\sigma_{q-q} = 1/9 \cdot \sigma_{NN}$) longitudinal momentum is transferred from one collision partner to the other and vice versa. Pions and other mesons are not directly produced, but result from the decay of excited resonances and strings. The decision how an excited state decays depends on its mass, e.g. nonstrange baryons are projected onto the experimentally given discrete resonances and decay according to the measured branching ratios if the mass is below 2 GeV/c². Higher mass states are assumed to be longitudinally excited and fragment either as independent strings or eventually — if several strings are overlapping — as highly charged flux tubes (ropes). The ingoing original constituent quarks continue to interact without any time delay, because these quarks are "dressed". In the spirit of the additive quark model their interaction probability remains unchanged while

they are traversing a medium. The secondaries appear after some formation time has elapsed. Their formation points are determined from the decay of resonances or the flux tube break points. After formation a secondary hadron can interact with all other particles.

Before we may hope to successfully deal with nucleus-nucleus collisions, a microscopic model has to be tested in the most basic case, the scattering of two hadrons. Let us therefore describe first the RQMD approach to high energy hadron-hadron interactions. In RQMD the most important interaction type is that two ingoing particles get each excited in a collision. A most striking feature of multihadron production is the limited transverse momentum transfer in hadronic collisions leading to a jetlike structure quite similar to the jets found in e^+e^- collisions. The dominance of longitudinal excitation is naturally accounted for in the fragmentation of colour strings which is the most successful approach to soft multiparticle production in hh , lh and l^+l^- collisions [1].

2.1 The elementary colour string

Using modern accelerators, experiments were designed to produce extremely high momentum quarks, e. g. in e^+e^- annihilations into a quark pair. The fact that no free quarks have been found even in these experiments but only "white" hadrons (colour singlets) indicates that the colour force possesses the particular property to become stronger with increasing distance between e. g. a quark and an antiquark. In contrast to QED the QCD colour field which is created by some source (e. g. a quark) is not allowed to spread out into the vacuum. The colour flux is compressed by the surrounding vacuum into a small region of space around the source (bag or flux tube). Even infinite momentum quarks cannot be freed, because the colour flux tube between the receding quarks starts to break via quark pair creation from the Dirac sea. This is the analogue of the well-known "decay of the QED vacuum" in the presence of an external electric field. Seen from one end of the flux tube the original quark combines with an antiquark which has been created by the colour field into a hadron. The created companion quark takes over the role of the original quark as the source of the colour flux:

$$q \rightarrow (q_1 \bar{q})M + \bar{q}_1 \quad . \quad (1)$$

The process indicated in (1) may be repeated several times giving rise to a whole *jet* of hadrons collimated around the axis of the original quark motion. Note that the tunneling process favors creation of quark pairs with low transverse momenta.

A quantitative description of this process has been done based on semiclassical *string fragmentation* in 1+1 dimensions (time and one space dimension given by the axis of quark motion). A one-dimensional string may serve as a simple model for a confined quark-antiquark pair. The energy density inside the created flux tube is

Figure 1: Yo-Yo in position space: at rest (left) and moving (right)

assumed to be constant which leads to a potential linearly rising with the distance between these two quarks. The Hamiltonian for massless quarks incorporating a linear rising potential can be written as

$$H = |p_1| + |p_2| + \kappa \cdot |z_1 - z_2| \quad . \quad (2)$$

The string tension κ has a value of $\kappa \simeq 1 \text{ GeV/fm}$ extracted from hadron spectroscopy and Regge trajectories. The classical canonical equations of motion can be derived from the Hamiltonian in eq. (2)

$$\begin{aligned} \frac{dp_i}{dt} &= -\frac{\partial H}{\partial x_i} = \pm \kappa \quad , \\ \frac{dz_i}{dt} &= \frac{\partial H}{\partial p_i} = \pm 1 \quad . \end{aligned} \quad (3)$$

Thus the quarks are always moving with the velocity of light and are winning or loosing a constant momentum κ per unit time. The corresponding Yo-Yo solution is pictured in fig. (1) for a $q\bar{q}$ pair in its rest system and a moving pair. A nice feature of the Yo-Yo is that the momenta of the $q\bar{q}$ pair can be simply read off from the space-time evolution of the Yo-Yo (see fig. (1)). The light cone momenta defined as

$$P^\pm = E \pm P \quad (4)$$

of the $q\bar{q}$ pair are given up to a normalization factor $\sqrt{2}\kappa$ as the sides of the rectangle formed by the quarks in the $t-z$ plane .

In fig. 2 the original Yo-Yo breaks into two pieces, because a pair $q_1\bar{q}_1$ is created screening the original quark charges. Again the momenta of the two fragments can be directly read off from the figure. There is one-to-one correspondence between string evolution in position and momentum space. This allows to formulate the fragmentation law in momentum space and thereby fix the location of all break points

Figure 2: Yo-Yo in position and momentum space. The string breaks due to creation of $q_1 \bar{q}_1$.

in position space which is important for space-time aspects of the dynamics. E.g. the hadron formation points are defined in RQMD as the arithmetic mean of the two creation points of the quarks forming the corresponding hadron.

The string fragmentation law in momentum space on which the LUND model is based and which is employed in RQMD follows the iterative structure of (1) by splitting the light cone momentum of the original quark:

$$p^+(\bar{q}) = p^+((\bar{q}q_1)_M) + p^+(q\bar{q}_1) \quad (5)$$

for a right moving and the corresponding negative light cone momentum for a left moving quark. The fragmentation function which determines the stochastic distribution of the old momentum onto the newly formed hadron and the remaining string piece gets a special functional form by requiring the left-right symmetry of the whole fragmentation process:

$$f(z) \sim \frac{1}{z} \cdot (1-z)^a \cdot \exp(-b \cdot m_t^2/z) \quad (6)$$

with z the momentum carried over to the new hadron and m_t the hadron (transverse) mass. Note that eq. (6) determines together with m_t which is related to the area of the hadron Yo-Yo the break point of the original string. The stochastic fragmentation process is repeated until the mass of the remaining string piece becomes too small for further string fragmentation and decays into two final hadrons.

2.2 String excitation in hh and hA interactions

In high energetic inelastic binary collisions a phenomenological $1/x$ law is used in RQMD for the transfer of light cone momentum fractions $p^+ = p^0 + p_z$. In the

Figure 3: Decaying hadronic string in position space. Four hadrons A - D are formed, their formation points indicated by dots. Thick lines give the trajectories along which the hadrons, respectively in the beginning the original constituent quarks, are propagated. p_L^+ , $p_{Y_o Y_o}^+$, and p_B^+ are the forward light cone momenta for the leading (spectator) quark, for string excitation and for the interacting (backward) quark. $p_{T_a}^-$ is the backward light cone momentum which has been transferred from the target.

collision both particles get new light cone momenta

$$\begin{aligned} (p_1^+, p_1^-) &\rightarrow (p_1'^+, p_1'^-) \\ (p_2^+, p_2^-) &\rightarrow (p_2'^+, p_2'^-) \end{aligned} \quad (7)$$

The longitudinal direction refers to the direction of particle motion in the two-body CMS. The old light cone momentum pair has a large and a small component for every particle (depending on the sign of p_l). The new value of the small light cone component scales according to the probability distribution

$$dP \sim \frac{dp_l'}{p_l'} \quad (8)$$

The other component is given by momentum conservation.

RQMD follows the so called recombination approach in hh collisions (see [2] for a discussion of fragmentation and recombination models). One of the ingoing two triplet charges in a hadron remains a spectator and neutralizes its colour by picking up a $\bar{3}$ in this approximation $x = 0$ quark from the sea without losing momentum. Therefore the measurable leading hadron momentum distribution directly reflects the spectator constituent quark momentum distribution. The idea behind is that hadronic strings with constituent quarks at the ends fragment differently from e^+e^- generated partonic strings: The constituent quarks are much better prepared for

hadronization than partons, and therefore the leading particles in hadronic collisions carry more longitudinal momentum than – in the average – e^+e^- induced hadron jet production. Obviously only spectator quarks are able to transfer all their momentum to the hadron which contains them. Hadrons formed from interacting ingoing quarks or quarks which are created by string breaking get their momentum according to the usual rules of string fragmentation [3]. The parameters of the string fragmentation scheme are fixed from e^+e^- data and give good agreement with the experimentally observed particle multiplicities, rapidity distributions and transverse momentum spectra in binary collisions between nucleons, pions and kaons. A decaying hadronic string in position space – according to the RQMD propagation – is shown in fig. (3). Note that the string topology in position space is slightly more complicated than a Yo-Yo. The interacting quark continues its motion into the forward direction, because a sudden reversal would mean that it has instantaneously lost all its momentum which seems to be incompatible with the nature of *soft* momentum transfer in interactions.

Earlier RQMD versions used the default description of the JETSET subroutines [3] to determine the forward (leading) quark momentum. However, inspection of experimental data shows that the momentum distribution generated by JETSET (having the same functional form which is used to determine first rank hadrons from e^+e^- strings with modified parameters “hardening” the distribution) does not describe the experimental data very well [4]. The x_F -distribution of protons is essentially flat in pp collisions while JETSET generates a maximum at $x_F = 0.6$. For the most recent version of RQMD (RQMD 1.08) a constituent quark momentum distribution of the following functional form is chosen:

$$f_q(z) \sim \sqrt{z} \cdot (1 - z)^3 \quad (9)$$

represents the distribution for the momentum fraction of the single quark and therefore

$$f_{qq}(y) = \int_0^1 dz \delta((1 - z) - y) f_q(z) \quad (10)$$

gives the corresponding diquark momentum fraction. The two constituents of a diquark may end up in different hadrons if the diquark splits. We therefore need the internal momentum distribution of each quark in the diquark. We have chosen the functional form

$$f(z) \sim z \cdot (1 - z), \quad (11)$$

because each quark is expected to carry half of the diquark momentum on average. The choice of the momentum distributions in eqs. (9),(10) and (11) is motivated by the functional similarity to valence quark distributions in the low Q^2 regime for $z \rightarrow 1$ [5] and by their mean values (0.27 and 0.73), which are near to the naive expectations 1/3 and 2/3. As can be seen from the Λ distribution in fig. 4 the Monte Carlo procedure makes the resulting – effective – distribution softer than given by eq. (10), because it falls more often to fragment a string successfully if z is in the vicinity of 1 (and

Figure 4: Feynman- x_F distribution for $p(205\text{GeV}) + p \rightarrow p + X, \Lambda + X$: comparison between RQMD 1.08 (straight line for protons, dashed line for Λ 's) and experimental data (circles, squares). The data were taken from [6] (protons) and from [7] (Λ 's). The difference in the shape for $x_F \rightarrow 1$ between protons and Λ 's is mostly caused by the diffractive contribution to the protons.

of 0). It is assumed that the constituent diquark ends up in the outgoing baryon with probability 0.5 (case a), otherwise a single quark only (case b) due to diquark splitting.

$$\begin{aligned}
 \text{a)} \quad q_1 q_2 &\longrightarrow (q_1 q_2 q_3)_B \bar{q}_3 \\
 \text{b)} \quad q_1 q_2 &\longrightarrow (q_1 \bar{q}_3)_M (q_2 q_3) \\
 &\qquad\qquad\qquad \hookrightarrow (q_2 q_3 q_4)_B \bar{q}_4.
 \end{aligned} \tag{12}$$

Fig. 4 shows that the baryon distribution in pp collisions resulting from RQMD 1.08 is rather flat in accordance with experimental data.

The RQMD excitation law in hadronic interactions is quite similar to the Lund model FRITIOF [8] – in contrast to the dual parton approaches in which the interaction proceeds via colour exchange. However, if a projectile experiences more than one inelastic collision the string topology in RQMD becomes different from the Lund model. In FRITIOF there is only one projectile string whose topology is fixed by the remaining projectile momentum and the backward momentum gained from the target. In RQMD every constituent quark interaction generates a new Yo-Yo type string piece. In case of leading quark interaction the backward momentum is “sandwiched” between two forward going momenta, the momentum carried by the constituent quark and residual projectile momentum (originating e.g. from the backward constituent quark). Such a structure of momentum ordering corresponds classically i.e. without string breaking to a *folded string*. A classically evolving string can be represented as a function of two parameters (usually one time and one energy

Figure 5: Interacting constituent quark in position space. q_0 interacts at point C which leads to a formation of a new Yo-Yo. For clarity the original string which the interacting quark q_0 and after the interaction point q_1 is trailing behind is not fully drawn, and the newly created Yo-Yo $(q_0\bar{q}_1)$ has been left stable. Quark trajectories are dotted for noninteracting partonic quarks and are thick straight lines for interacting constituent quarks.

parameter, t and ω) in Minkovski space [9]. The initial condition for the “sandwich” case reads

$$\begin{aligned} x(t=0, \omega) &= x_{coll} & \forall \omega \\ \dot{x}(t=0, \omega) &= \begin{cases} p_{cq}/E_{cq} & \omega \in (0, E_{cq}) \\ p_{Ta}/E_{Ta} & \omega \in (E_{cq}, E_{cq} + E_{Ta}) \\ p_{res}/E_{res} & \omega > E_{cq} + E_{Ta} \end{cases} \end{aligned} \quad (13)$$

with p_{Ta} , p_{cq} and p_{res} the momentum transferred from the target, the constituent quark and the residual projectile momentum. The classical string equations of motion would give a “hair needle” type solution for the initial condition in eq. (13). A point inside a string which carries a finite amount of momentum is usually called a *kink*. However, for a description of constituent quark interaction one has to go beyond the classical string solutions (see fig. 5). The backward momentum which is transferred to a forward moving constituent quark polarizes a quark pair from the constituent quark sea. One sea quark replaces the constituent quark as the source of colour flow (end point) in the former existing string. The corresponding anticharge is pulled backward by the momentum transferred from the target, and it forms a new Yo-Yo together with the original constituent quark.

A major difference between RQMD and other string models is the treatment of the momentum degradation of a projectile moving in a nucleus. RQMD contains basically

three dynamical features for nuclear collisions which are of relevance for the shift of the original projectile flavor and baryon number in momentum space: constituent quark interaction, diquark splitting and – more important for AA than hA collisions – interactions with secondaries. There are two extreme scenarios for the energy loss of leading (di-)quarks. In one scenario [10,11], the leading hadron after each collision was allowed to interact further while the other hadrons were produced with some time delay (leading particle cascade). Though it has the advantage of simplicity – every collision is like a “normal” hadron-hadron interaction – this scheme is not appealing, because there is no reason why no time is needed to form the leading hadron. The minimum formation time for creation of the hadron asymptotic states is expected to be – at least – not smaller than the passage time through a whole nucleus at ultrarelativistic energies. Other dual parton models and the Lund model have used the more consistent assumption that, while traversing the nucleus, a leading (di-)quark loses momentum only for string creation and *fragments afterwards* with the same law into a hadron as in elementary hh collisions [8,12,13,14]. In RQMD the original projectile momentum is redistributed after an elementary collision or equivalently after the first projectile collision in a nucleus: on the original constituent quarks, string excitation and for target excitation. When a constituent quark scatters a similar scheme applies [15,16]:

$$p^+(cq) = p^+(cq) + p^+(Y_0 - Y_0) + p^+(Ta) \quad (14)$$

with the difference that the new light cone momentum is always given by the string fragmentation function, because the corresponding constituent quark is no spectator any more. Eq. (14) provides a rather efficient energy loss mechanism for a hadron projectile in matter which is in between the two extremes mentioned above. In the fragmentation approaches the first two momentum contributions on the r.h.s. of eq. (14) are only split once after the projectile has gone through the nucleus, and only the momentum used up to excite the target $p^+(Ta)$ is subtracted in every collision. In the leading particle cascade the projectile momentum is redistributed similarly to eq. (14). However, the leading quark loses its momentum much faster than in RQMD, because it interacts with the leading hadron cross section in nuclear matter (in RQMD: σ_{qN}).

In RQMD 1.08 it is assumed that a diquark will split in a subsequent non-diffractive interaction in a nuclear target if it has not already done so in the first collision. In this case only one spectator quark with a short, nonexcited bond to the “junction” (the centre of a “mercedes star” type flux tube connecting the three quarks in a baryon) will be part of the baryon created in the fragmentation of a baryon string. The flavor flow is the same as indicated in case (12b) for diquark splitting in an elementary baryon-hadron collision, the difference being that $(q_1\bar{q}_3)_M$ now denotes a string, because the sea antiquark $\bar{q}_3$ is accelerated by the momentum transfer to the interacting constituent quark q_1 . The original diquark momentum is

also distributed on the two quarks q_1 and q_2 – the spectator quark – according to eq. (11). Therefore the baryon momentum distribution resulting from diquark splitting in sequential interactions in a nuclear target and in elementary baryon-hadron collisions is given by the same function, the single quark momentum distribution in a diquark eqs. (10) and (11). Again the momentum taken by the interacting quark q_1 is distributed according to eq. (14). If the remaining constituent quark with short bond to the baryon junction suffers subsequently a collision it may even happen that none of the original quarks ends up in the outgoing baryon.

2.3 String-string interaction

In earlier RQMD calculations, the excited strings were fragmented independently even if they were lying on top of each other. In RQMD 1.08 the fields of two or more strings are stochastically added in SU(3)-space if they overlap in the longitudinal direction and share the same transverse area. These fields have a larger strength than ordinary triplet-antitriplet flux tubes (colour ropes). This influences the composition of created quark-antiquark pairs, because the suppression of heavy quarks and of diquarks is weakened. The total pair creation rate and the flavor composition are calculated with the help of Schwinger's vacuum persistence rate for a constant chromoelectric field [17]. Casher, Neuberger and Nussinov were able to rederive Schwinger's formula using WKB methods, which also gives transverse momentum distributions of the created charges [18]. The force acting on a quark antiquark pair in the sea is given as the energy per unit length that is destroyed when the quark and antiquark move apart. This results in the following formula for the tunneling probability per unit time and unit volume – e.g. for an antiquark:

$$\frac{dn}{d^4x} = \frac{\gamma}{4\pi^3} \cdot (\kappa(p, q) - \kappa(p-1, q)) \cdot \sum_{\text{flavors}} \sum_{n=1}^{\infty} \int d^2p_t \frac{(P(p_t)^n)}{n}, \quad (15)$$

where $\kappa(p, q)$ and $\kappa(p-1, q)$ are the rope tension before and after charge creation, γ gives the colour degrees of freedom and $P(p_t)$ denotes the tunnel probability from a virtual to a real state calculated using the WKB method. In order to reproduce the suppression parameters for strangeness and diquarks, an interpolation between current and constituent quark masses is applied in eq. (15) [19].

Eq.(15) does not only give the relative tunneling probabilities but the absolute scale, too. We get a total break-up probability of $d^2p/dzdt = 0.315/\text{fm}^4 \cdot \pi \cdot r_s^2$ for elementary strings. Obviously the string radius determines the number of breaks per oscillation period. In the Monte Carlo implementation of the string and rope decay break points are stochastically sampled with the probability density given above. The quark pairs are created with zero longitudinal momentum, but afterwards they are accelerated in the force field of the outer charge. The rope fragmentation into colour singlets is more complicated than for elementary strings. For instance, a hadron from string decay always contains quarks from neighboring break points.

Figure 6: Schematic picture of a rope with colour charge (p,q) (on the right side). While the crossing of a quark trajectory with an antiquark trajectory always leads to hadron formation in elementary strings $((p,q)=(1,0))$ this is not the case in ropes (see case a). In a) $\overline{Q}_I$ and Q_{II} are pulled into different directions by the force created by the outer charges. E. g. for $\overline{Q}_I$ the force per unit length is at first $\kappa(p,q) - \kappa(p-1,q)$ and after crossing $\kappa(p-1,q) - \kappa(p-2,q)$. In case b) the two crossing charges form a white state (hadron) and experience no forces after their crossing point any more due to the rope charge. Case b) is stochastically chosen with a statistical weight given by the inverse of the possible screening configurations. This has the obvious consequence that a given charge may combine not later than with the last crossing anticharge into a white state, but earlier in contrast to [20]. Note that Q denotes the colour charge and therefore means quark as well as $3-\overline{q}\overline{q}$ which are together with their anticharges the building blocks of the colour multiplets.

This can be different for ropes (see fig. 6). The equations of motion for the quarks are the same – properly generalized to arbitrarily charged ropes – as given in [20] for the case of two charges. Differently from [20] we allow at crossing points of a charge and an anticharge the combination into a colourless state which separates from the rope without further interaction (as can be seen in fig. 6). The probability for this to happen is given by the inverse number of available “screening” configurations. At last the final string pieces with given flavors at the end points are projected onto the basic hadron multiplets (like in the LUND model). Finally neighboring string pieces are brought on shell via zero degree angular scattering, because they do not have correct hadron masses. We compared the total charged particle multiplicities from string decay in a mass range up to 10 GeV/c² to e^+e^- experiments. A transverse radius of 0.8 fm gives good agreement with the experimentally determined charged particle multiplicities [21].

2.4 The hadronic resonance dominated interactions

Schematically there are three different energy regions in hadron-hadron interactions: the (quasi-)elastic scattering, the region of resonance production and formation and the high energy region characterized by abundant production of particles. In the resonance region the kinetic energy of the reaction partners is sufficient to form excited states of the ingoing hadrons which subsequently decay again into the stable hadrons. The most prominent examples are

Note that in case of most meson-baryon and meson-meson interactions the formation of a *single* resonance is possible, but never for baryon-baryon interactions, because the total quantum number in the initial state would give an exotic hadronic state ($B = 2$). Reactions like in eq. (16) are contained in RQMD. They are calculated with the help of the Breit-Wigner formula for s channel resonance formation or via one-meson-exchange in the t channel. Resonance dominated reactions are important in nucleus-nucleus reactions up to the highest beam energies, at least in later stages of a collision – after two nuclei have passed through each other and the expanding system may be characterized as a hadron gas. The system cools due to expansion leaving only those hadrons correlated in position space which have similar velocities. Therefore the internal typical excitation energies are very moderate before hadronic freeze-out. Resonance formation influences the particle momentum distributions (e.g. the p_t spectra). The particle chemistry may change, too, distorting signatures from earlier reaction stages, e.g. due to reactions like

$$\pi\pi \longleftrightarrow S^*(970) \longleftrightarrow K\bar{K}$$

Now we describe the determination of interaction probabilities involving *ingoing resonances*. It is in the nature of resonances that their reaction rates with other hadrons are experimentally not easily accessible. Therefore we must rely on some model for these processes. We may distinguish the different classes of interaction according to the number of ingoing (anti-)baryons: BB , BM , MM and $\bar{B}B$ (B denoting baryon, M denoting meson).

In the high energy region (characterized by a plateau in the cross sections for known hadronic reactions like πN , KN or NN) differences between resonances and ground state hadrons become practically irrelevant. The difference in the masses does not matter any more for the kinematics, spin has no effect on the bulk of the production processes. Even different flavors show up only in the fragmentation region, but not in the central region where most of the particles are produced (universality in high energy hadronic collisions). Therefore we expect that the same string excitation and fragmentation scheme for these interactions can be applied reliably as for reactions which are experimentally accessible. The cross sections for unknown reactions in the high energy region are determined by the additive quark model (the strange quark has a cross section 40 % smaller than an u or d quark) and from Regge theory [22]:

$$\sigma_t = 40 \cdot \left(\frac{2}{3}\right)^{(M_1+M_2)} \cdot \left(1 - 0.4 \cdot \frac{S_1}{3-M_1}\right) \cdot \left(1 - 0.4 \cdot \frac{S_2}{3-M_2}\right) \text{ mb} \quad (18)$$

$$\sigma_{el} = 0.039 \cdot \sigma_t^{3/2} \text{ mb.} \quad (19)$$

$M_i = 1(0)$ for a meson (baryon), S_i gives the number of strange quarks in the corresponding hadron ($i = 1, 2$). One source of uncertainty might be the choice of the total cross sections for resonances, because internal excitations show up in a larger transverse area. The cross sections in this energy region are essentially determined by geometry.

If no information is available on an interaction type involving one or two resonances it is assumed that the outgoing channels (mass excitation, angular distribution, ...) are given by the same scheme as for the corresponding ground state hadrons. There are notable exceptions, e.g. in the baryon-baryon sector the modification of every BB cross section due to the difference between the $NN \rightarrow BB$ cross section and the reversed cross section (extracted via detailed balance). BB cross sections involving only Delta's and nucleons are calculated in the framework of the one-meson-exchange approach: $NN \leftrightarrow N\Delta$, $\Delta N \leftrightarrow N\Delta$, $\Delta N \leftrightarrow \Delta\Delta$.

The formation of s channel resonances is calculated in the MB and the MM sector from multichannel Breit-Wigner formulae and — above some C.M. energy for which a description in terms of discrete resonance levels becomes impossible — from

a cross section which is decreasing as $1/\sqrt{s}$. Let us exemplify this for nonstrange baryon resonance formation which is experimentally well explored in πN collisions. In the low energy region these reactions become inelastic, but the interaction is known to be dominated by s channel resonances. If the baryon resonance parameters are determined with high precision one can reliably extract transition rates between experimentally inaccessible channels like $\rho N \rightarrow YK$. We assume that up to some limiting CMS energy the meson-baryon interaction is completely dominated by s channel resonance formation. Thus we neglect some t channel background processes except for πN where we extracted an elastic background – up to 5 mb – from experimental data and for channels like KN in which resonance formation is forbidden. The value below which we consider only resonance formation is set to $\sqrt{s_0} = 1.8$ GeV for N^* formation and $\sqrt{s_0} = 2$ GeV for formation of Δ^* (and Y^*). We use a generalized Breit-Wigner formula for the cross section

$$\sigma_{MB \rightarrow B'} = b \cdot \frac{\pi}{k^2} \cdot \sum_R \frac{(2J_R + 1)}{(2S_1 + 1)(2S_2 + 1)} \cdot \frac{\Gamma_R(MB) \cdot \Gamma_R(\text{tot})}{(\sqrt{s} - m_R)^2 + \Gamma_R(\text{tot})^2/4} \quad (20)$$

The sum runs over all resonances which are given in table 1 (with a mass below 2 GeV/ c^2) and the Δ . The resonance masses and decay parameters are based on the listing of the Particle Data Group [23]. b is a factor normalizing to the πN resonance formation cross section for MB equals πN . (As stated above the resonance formation cross section in πN is the total πN cross section minus an elastic background determined by a consistency condition that background plus elastic resonance decay equals the elastic πN cross section.) $\Gamma_R(MB)$ denotes a partial decay width into the channel with meson M and baryon B . The decay widths are $\sqrt{s}$ -dependent via the relative momentum in the CMS of the decaying resonance k

$$\Gamma_R(MB) \sim m_R/\sqrt{s} \cdot k^{(2l+1)}/(1 + 0.2 \cdot (k/k(m_R))^{2l}) \quad .$$

This ensures the correct threshold and high energy behaviour of a particular channel. In a meson baryon annihilation the quantum numbers of the formed resonance are chosen according to the relative weight of the corresponding Breit-Wigner term in the sum of eq.(20). It has been checked that an application to πN collisions reproduces approximately the hyperon-kaon production cross section and the total pion yields in inelastic collisions [24].

Most important in nuclear collisions – e.g. for strangeness creation – is secondary meson-baryon scattering in the intermediate CMS energy region $s = 4 - 16$ GeV². Here kinematical differences between resonances and ground state hadrons are still significant, but the resonance level density is too high for an experimental determination of resonance parameters and multiparticle channels are open. A Regge-motivated $1/\sqrt{s}$ -dependence of the annihilation cross section for πN and KN is assumed starting from the $\sqrt{s_0}$ values given above. The exponent $1/2$ for the s behaviour has been chosen here, because a Schwinger-type decay of the flux tube gives another suppression

factor $1/s$ for decay into two particles. Thus we get from this model a $s^{-3/2}$ behaviour for flavor changing two body reactions (corresponding to an “average” exponent $3/2$ extracted from πN data).

The Breit-Wigner tails of the discrete resonances – with mass below $2 \text{ GeV}/c^2$ – decrease much faster with s than the total annihilation cross section. The gap is filled by a coupling of πN and $\bar{K} N$ to a “resonance continuum”. Above a mass of $2 \text{ GeV}/c^2$ the baryon resonances are less well-known. However, the density of states is expected to increase strongly. This allows to replace a discrete spectrum by a continuum of states with averaged couplings to various MB channels. We take the values for these MB couplings from color flux tube phenomenology [3], because a smooth transition from string to heavy resonance decay is expected [18]. Thus the annihilation cross section of other MB channels is proportional to the πN annihilation cross section; the proportional constants are the ratio of the usual spin factors and Clebsch-Gordon coefficients, relative CMS momenta (squared), the “infinite energy” flux tube couplings and phase space factors $Erf(p_{max}/\sigma(p_t))$ derived from the p_t distribution (here: Gaussian with width $\sigma(p_t)=0.4 \text{ GeV}/c$) accompanying pair creation in a flux tube. Taking the MB couplings from flux tube phenomenology is consistent with the fragmentation of the “continuum states” in RQMD, because these states, which may also be produced in non-annihilation two-body-type interactions, decay stringlike. Their decay is based on a string fragmentation scheme with parameters fixed from e^+e^- and lepton-nucleon collisions. In [24] it is shown that the string model is able to describe the coupling to states like $\Delta\omega$ and $\Delta\eta$ in πN collisions very well. This gives us reason to believe that the coupling of those resonance channels to strange hadrons is described as well. It is interesting to note that we must use a larger s quark suppression for flux tube decay into two strange hadrons (0.2 instead of 0.3). This is expected from microscopic calculations giving a larger suppression for heavy mass quarks if the string breaks very early [25]. While the meson-baryon (resonance) annihilation probability goes down with $\sim 1/\sqrt{s}$ the nonannihilation contribution is switched on with the same functional behaviour to ensure a smooth transition between the low and high energy regime.

3 Baryon number flow

At A15 experiments with 10 AGeV and 14.5 AGeV Silicon beams on various targets have been performed and analyzed, experiments with a gold beam are under way. In fig. 7 we show proton momentum distributions for inelastic p and light ion projectile collisions at 14.5 AGeV. They are directly compared to experimental data [26]. The agreement between RQMD and E802 data for the proton stopping and the particle production is very good in pA interactions. There has been intensive discussion in the past whether the discrepancy which is visible in the comparison of the E802 data for Si+Au and the RQMD calculations (and also other model results) signals

Figure 7: Calculated and experimental meson rapidity distributions for minimum bias $p + \text{Be}$ (left), $p + \text{Au}$ (middle) and central $\text{Si} + \text{Au}$ (right) reactions at a projectile energy of 14.5 AGeV. The histograms represent the RQMD results: protons (solid line) and π^+ (dashed line). The experimental data are shown for protons as circles and for π^+ as dots. The $\text{Si} + \text{Au}$ distributions are divided by 28.

an unexpected large amount of transparency in those reactions or might be due to trigger effects and normalization problems in the experimental set-up. A recent remeasurement of the proton spectra by E802 has been done with the result that the larger fraction of the original discrepancy has disappeared now [27].

The RQMD calculations were done with quasi-potential interaction between the baryons included [28,29]. We used Skyrme-type potentials giving strong repulsion at high densities. The repulsion in an excited baryon resonance gas is not well determined. In order to get good agreement with the proton transverse momentum slope (measured by E802) the attractive part of the quasi-potentials between NB and DD (N=nucleons, D= Δ , B=other baryon resonances) was switched off [29]. The slope parameters T in an exponential fit to the RQMD generated transverse mass distributions in the interval $0.3 \text{ GeV} < p_t < 0.9 \text{ GeV}$ = 221 MeV (protons), 166 MeV (pions) and 214 MeV (kaons) are in accordance with the experimental findings [26]. While the pions are less affected by the pressure induced flow the protons clearly exhibit the presence of strong pressure due to the quasi-potentials. If confirmed by future measurements – eventually of even higher mass particles like deuterons – the analysis of the p_t spectra might become a very useful “baryometer” in nucleus-nucleus collisions at AGeV. Note that even the longitudinal momentum baryon distributions are affected by the repulsion built up in the high density region. Baryons are pushed away from the center of the fireball by giving them a longitudinal momentum kick.

Let us now turn to collisions between heavy nuclei. Experiments with a heavy symmetric system (Au on Au) are currently undertaken at the AGeV booster. Fig. 8

Figure 8: RQMD 1.07 calculation of final rapidity distribution in Au(11.7 AGeV) + Au reactions ($b < 3\text{fm}$): protons (left) and mesons (right: π^+ solid line, K^+ dashed line histogram)

shows the RQMD predictions of the final nucleon and meson rapidity distributions at $p_{\text{lab}} = 11.6 \text{ AGeV}/c$. As the strong pile-up of baryons at midrapidity shows RQMD predicts for such systems complete baryon stopping [30] which is the key to achieve high baryon density in the intermediate stage of a collision.

The achievable baryon density in a central collision between two heavy nuclei at AGS energy which has been extracted from RQMD calculations exceeds its kinematic “free streaming” limit $2\gamma \cdot \rho_0$ by far [30]. This can be understood as a shock compression due to multiple collisions with a density pile up. It is found that for central Au + Au collisions the volume of extremely high thermalized energy density ($> 1 \text{ GeV}/\text{fm}^3$) exists for a time interval of around $8 \text{ fm}/c$. Afterwards the volume of high density drops quickly. The “macroscopic” high density region in central heavy ion collisions has roughly double the life time than in case of Si on Au collisions.

Baryon stopping and creation of a baryon dense region may lead to macroscopic, collective behaviour predicted on the basis of the fluid dynamical model [31]. Collective flow may be observable even at these ultrarelativistic energies. This in turn is of vital importance for diagnostic purposes: The predicted bounce-off and squeeze-out effects can be used as barometers to measure the pressure built up in the hot dense participant matter. The bounce-off e. g. can be quantified via the measurement of the directed in-plane transverse momentum transfer which has been widely used at BEVALAC energies [32]. In fig. 9 we present the RQMD results for the reaction Au(11.7 AGeV) on Au which demonstrates that strong flow effects can be observed. This prediction could be tested if the reaction plane could be determined, e. g. by

Figure 9: The mean p_x of the nucleons as a function of the rapidity. p_x is the projected transverse momentum in the collision plane. The reaction is Au on Au at 11.7 AGeV beam energy with impact parameter $b < 3\text{fm}$. The influence of repulsive potentials (solid line) is shown in comparison with a pure cascade calculation (dashed line histogram).

measuring the azimuthal distribution of forward and backward going baryons at the same time. The experimental detection of collective flow would be a dramatic signal for the formation of a ultradense state of matter.

It is expected that with increasing incident beam energies – e. g. at CERN energies (60 and 200 AGeV) – the maximum energy densities which could be reached may even be larger than at AGS. However, it is unknown whether the colliding nuclei become more or less transparent to each other. The recent S- and O-induced light ion reactions provide a crucial test to distinguish between two extreme pictures of the dynamics, the Bjorken scenario of “transparent” nuclei and Landau’s complete stopping scenario.

We infer from the RQMD results that there is a strong mass dependence of the stopping power at CERN energies as well as at AGS energies. The proton rapidity distributions of S + S and Pb + Pb which were calculated with RQMD 1.07 show – see fig. 10 – a huge amount of stopping for the final protons in the heavy system, but not in the light ion reaction. We extracted the number of collisions per hadron which is an indicator of thermalization in a reaction (see fig. 10). Notice that in the central region not only the original nucleons, but also produced secondaries like antinucleons experience more than ten collisions. The RQMD results for the nuclear stopping power at 200 AGeV are confirmed by recent NA35 measurements of the proton distribution in central S+S reactions. As it is shown in fig. 10 the measured distribution in the S + S reaction is in good agreement with the calculation. The RQMD calculations indicate that a quark gluon plasma – if created at all in these

Figure 10: RQMD 1.07 calculations of final proton rapidity distribution in S(200A GeV) + S and Pb(160A GeV) + Pb (upper two plots) (histograms). The dots (for S + S) are proton data from the NA35 group for very central collisions ($\sigma = 34$ mb) [33]. The centrality trigger was minimum energy flow into the forward direction (FET trigger). The trigger conditions have been simulated in the RQMD calculations. The two plots below show the rapidity dependence of the mean collision number for (anti-) nucleons in these reactions.

Figure 11: RQMD 1.07 calculations of final net baryon (left) and meson (right: pions – solid line, kaons – dashed line histogram) rapidity distribution in central Pb+Pb, $\sqrt{s} = 200$ AGeV.

future CERN experiments – would have to be rather baryonrich.

Will heavy ion collisions at collider energies create the ultrahot, baryonnumber free region which can be directly compared to the baryochemical potential $\mu = 0$ lattice QCD calculations? Fig. 11 shows the results of the RQMD 1.07 calculation for $Pb + Pb$ at $\sqrt{s} = 200$ AGeV (RHIC) [34]. The nuclei suffer a mean rapidity shift of 2.6 units in rapidity. The mid rapidity region is apparently not baryonfree. The value of dN/dy at y_{mid} amounts to about 60 % of the value at the maxima. Two units of rapidity are lost in baryon-baryon interactions, which reproduces the value obtained in proton nucleus scattering. The rapidity distribution of pions and kaons is shown in fig. 11. One realizes that there is no plateau in the meson rapidity distribution (as would be present if the Bjorken scenario were applicable), but there is a pronounced peak. However, it is most important that also locally there is no plateau in the meson rapidity distribution. To measure the asymmetry of the local meson rapidity distribution in the neighborhood of a baryon we studied the mean value rapidity difference of colliding mesons and baryons. The quantity $\delta = sign(y_B) \cdot (y_B - y_M)$, which determines whether the meson rapidity is closer to midrapidity than that of the baryon it collides with, should be zero if the local meson rapidity distribution were symmetric. However, we find in our calculations a value $\langle \delta \rangle = 0.42$, indicating that in the mean any meson hit by a baryon has a rapidity 0.42 units closer to midrapidity than the baryon itself. The “width” of the local meson rapidity distribution which is given by $\sqrt{\langle \delta^2 \rangle}$, is found to be ≈ 1.55 (observe that this must be larger than δ itself in order to be consistent!). This of course immediately explains why there is a finite rapidity loss of the baryons to the mesons due to the

meson-baryon rescattering. In the RQMD 1.07 calculation 0.6 units (i.e. 25%) of the total rapidity loss come from the rescattering of the baryons with mesons due to this effect. The value $\delta = 0.42$ also means that coordinate-space and momentum-space are not correlated one-to-one. Thus we encounter for heavy ion induced reactions at RHIC energy contradictions to the validity of Bjorken's basic assumptions: There is no local (nor global) plateau in the secondaries' rapidity distribution and there is also no one-to-one correlation between coordinate space and momentum space, but the width of the local longitudinal momentum distribution has a rather large value up to between one and two units in rapidity. The RQMD calculations open up the possibility that the initial rapidity gap at RHIC energy (10 units) may not be sufficiently large to create a baryonnumber free hot fireball. However, measurements of baryon distributions varying the energy and mass dependence are necessary to settle the question of the "stopping power".

4 Strangeness

Strangeness enhancement seems to be one of the promising signatures for a quark-gluon plasma [35]. While the fractions of strange particles in an thermally equilibrated hadron gas and quark-gluon plasma are not very different, the reactions creating strange quark pairs proceed much faster on the quark-gluon level than on the hadronic level (reflecting the mass difference between strange and up or down quarks versus kaon and pion mass on the other side).

4.1 Rescattering contribution to strangeness

Strangeness enhancement has been observed in the recent light ion induced reactions at AGS and CERN. K/π enrichment was found in $S(200A\text{GeV})+W$ (NA34) and in $Si(14.5A\text{GeV})+Au$ (E802). Lambda enhancement has been reported for $S(200A\text{GeV})+S$ (NA35). A strong source of strange antibaryons seems to be present in the 200A GeV experiments. Both, antilambda and anticascade yields are seen in central collisions at a multiple rate compared to the expectation from naive pp extrapolation (NA35, WA85).

Some of the observed strangeness enhancement in central nucleus-nucleus reactions has already been similarly found in minimum bias hadron-nucleus collisions. A strong conversion of (presumably) target nucleons into strange baryons has been measured [36,37,38,39] for those reactions at 200 GeV, roughly a factor of two higher than what is expected by counting the number of target nucleons hit by the projectile and multiplying with the conversion factor of the elementary hadron-nucleon reaction. The HELIOS group has made a complementary measurement of charged kaons and antikaons confirming those measurements indirectly, because far more additional kaons than antikaons are detected in p nucleus reactions [40]. The Λ enhancement

observed as well in the target fragmentation region in S+S collisions by the NA35 group [36] suggests a common dynamical mechanism in hA and AA reactions. We are going to explore in the following whether secondary cascading inside the target matter is the dynamical mechanism responsible for Λ /kaon enhancement in pA and AA reactions. However, there are suggestions that the doubling of the Λ yields in AA collisions at 200 AGeV might be due to an effect which is exclusively present in AA collisions: leading diquarks which fragment into baryons in elementary hadronic collisions, but split in collisions on nuclear targets when suffering a subsequent interaction [41]. This gives roughly double the chance for an s quark replacing one of the original valence quarks in the projectile nucleon. In pA collisions this mechanism does not give Λ enhancement in the target fragmentation region, because only the projectile suffers more than one high energetic interaction.

Let us first consider the strangeness production in proton-nucleus collisions. Our motivation is that hA interactions provide a link between hh and AA collisions. pA collisions are a much cleaner testing ground for medium effects in strong interactions than AA reactions. In the former case the medium is fixed to be a groundstate nucleus, while in the latter case the medium created has rather unknown properties. A true understanding of strangeness production in nucleus-nucleus collisions can only be reached if the production mechanism in hA collisions is understood as well. Nikolaev argued that the Λ enhancement in p(200 GeV)+A can be explained by secondary rescattering [42]. However, lacking a complete dynamical description of hA collisions he was not able to give evidence that the assumed source of Λ production – $\bar{K}$ and π nuclear cascading – is compatible with the measured mass dependence of charged particle distributions. If the secondaries can create strange quark pairs they might more easily create additional pions. The strangeness suppression in π N interactions above the ΛK threshold is rather strong. While approximately one additional pion is produced, the kaon yields are in the few percent range. This is due to s channel resonance decay in this mass range mainly into a nucleon and two final pions and rarely into strange hadrons. If the linear volume dependence of Λ yields – $\sim A^\alpha$ with $\alpha = 0.94-1.06$ – in p(200 GeV)+A which has been measured by NA5 (at CERN) and E565/570 (at FNAL) were mainly due to π N interactions we therefore would expect a similar A^α component in the pion yields which, however, is absent [43].

The interaction of resonances is a major source for enriching strangeness in nuclear collisions. In contrast to π N, other meson-baryon interactions forming the same resonances enrich strangeness, because – in a small percentage of all interactions – they produce a hyperon and kaon, but they do not increase the net number of pions in the system.

In the intermediate stage of hadronic and nuclear collisions a large fraction of mesons and baryons are resonances. Pion mediated strangeness creation is kinematically strongly suppressed due to the large mass difference between kaons and pions, while reactions involving nonstrange resonances are much more favorable. Some of

Figure 12: Comparison between RQMD calculations (histograms) and NA35 data (squares and circles) for the rapidity distributions of neutral strange hadrons (Λ , K_S and $\bar{\Lambda}$) produced in p(200 GeV) on sulphur. The trigger condition is more than 5 charged particles in the streamer chamber acceptance.

the reactions are even exothermic like $\rho N \rightarrow \Lambda K$.

In figs. 12 and 13 the RQMD results are compared to experimental measurements by the NA35 group (p+S, p+Au). The calculated rapidity distributions follow very closely the trends in the experimental data. Note the strong asymmetry in the Λ distributions (the peak in the target fragmentation region) compared to the K_S and $\bar{\Lambda}$ distributions. It is remarkable that there is no local maximum for the Λ distribution in the projectile hemisphere any more – in the calculations as well as in the data. This applies even for the small system sulphur, though in p+p most of the Λ 's in the projectile fragmentation region are concentrated around $y = 4.8 \pm 0.2$. The good agreement found in the Λ stopping between experiment and RQMD calculations confirms that RQMD contains a realistic energy loss mechanism for leading hadrons.

There seems to be a small overestimation of the K_S yields in the events generated by RQMD. This is, however, no nuclear effect but can be traced back to higher K_S multiplicities in elementary pp collisions. RQMD gives 0.2 K_S 's per pp event to be compared to 0.17, the experimental number [44].

Where do Λ 's and the other strange hadrons come from in p+A collisions? In fig. 14 we show the sources of the finally observed strange particles for the system p(200 GeV) on gold in which nuclear effects are most clearly visible. Note that the sum of the various distributions does not exactly sum up to the total Λ and $\bar{\Lambda}$ yields. Roughly 10 percent come from multiple strange baryons and strange baryon resonances which decay into lambda's after the nuclear cascade is finished. Their source is not traced back in the calculation. Furthermore only the most important contributions are shown for the different species. It is obvious from fig. 14 that in addition to the Λ

Figure 13: Comparison between RQMD calculations (histograms) and NA35 data (squares) for the rapidity distributions of Λ (left), K_S (middle), and $\bar{\Lambda}$ (right) produced in minimum bias reactions $p(200 \text{ GeV})$ on gold.

contribution from baryon-baryon collisions (which are mostly collisions between the projectile and target nucleons) there is an equally important component in the target region due to secondary (meson) scattering with baryons (predominantly nucleons). We distinguished between Λ 's produced by πN , $\bar{K}N$ and other meson-baryon reactions to underline the statement that the interaction of resonances is more important than the first two channels. The nuclear cascade of pions and antikaons alone cannot explain the doubling of the Λ yields in the target region. Because of strangeness conservation the strong rescattering component has to show up in the kaon yields (also shown in fig. 14). One notices a characteristic difference in the rapidity distribution of kaons versus antikaons. This is caused by the slowing down of the projectile which is more important for antikaons than for kaons. Antikaons can only be made together with - at least - one kaon, but the smaller difference between hyperon and nucleon mass favors associated kaon production. The last point also favors kaons (and Λ 's) over antikaons in secondary scattering. Therefore the nuclear effects can be much more clearly seen in the Λ than in the K_S distributions which are an equal mixture of neutral kaons and antikaons. In fig. 14 we have shown additional source terms, contributions due to rope formation and meson-meson scattering which are both clearly suppressed compared to the dominant production mechanisms based on baryon interaction in $p + A$. Both - ropes and meson-meson interactions - contribute symmetrically to kaons and antikaons, but every contribution is only shown once in fig. 14. Note that the rope formation does not enhance (anti-)kaon yields in $p + A$. We have calculated that even in $A + A$ collisions rope formation does not directly result in more kaon production, because there are two opposing effects: the strangeness suppression is weakened in ropes due to the higher chromoelectric fields, but rope decay is faster than single string fragmentation leading to decreasing hadron multiplicities.

The HELIOS collaboration has measured very recently *charged* kaons and pions [40]. Their findings are very consistent with the RQMD results presented in this article. They measured ϕ (and S) reactions with W in the rapidity region $1 < y < 1.5$ which is most relevant for an observation of the rescattering effect (see fig. 14). While the HELIOS collaboration measures a clear increase in the K^+/π^+ ratio (compared to pp) they find no significance for enhancement of K^-/π^- . Our results for the system $p+Au$ which is very similar to $p+W$ measured by the HELIOS group compare well with the experimental data: K^+/π^+ 13 percent (to be compared to 14.1 ± 0.8 from the HELIOS measurement), and K^-/π^- 4.3 percent (HELIOS data 3.7 ± 0.4).

As we will show later on the secondary scattering mechanism provides – together with string-string interaction – not only an explanation of the strange particle yields in proton induced, but also light ion induced reaction at 200 AGeV. Before doing this we would like to mention that there is a striking similarity in the K/π ratios – and the K/p ratios (!) – at rapidity $y \sim 1$ in light ion induced reactions at AGS and at CERN, despite the rather different beam energie (14.5 and 200 AGeV). This seems to point towards a similar reaction mechanism which can be understood from the RQMD calculations. Meson-baryon induced kaon and lambda enhancement as suggested by the RQMD calculations is proportional to the meson density as well as to the baryon density. The typical rapidity shift of target nucleons in these reactions is only slightly more than in pp reactions (around one unit). The proton rapidity density at $y = 1$ therefore measures the number of target participants. On the other side the relevant meson density is given by their yields at rapidities below or near $y = 2$ [24]. Even faster mesons are mostly formed outside the target at 200 GeV and do not contribute to the cascading inside the excited target matter. Thus the much larger rapidity gap between projectile and target at 200 AGeV (six units) and the higher rapidity density at midrapidity $y = 3$ are of minor importance for the kaon/Lambda enhancement around $y = 1$ explaining the similarity to strangeness enhancement found at 14.5 GeV.

The RQMD calculations for central $Si(14.5\text{ AGeV})+Au$ reactions show a significant kaon and Λ enrichment caused by hadronic rescattering (see fig. 15). In [45] we have shown that the experimentally observed mass dependence of kaon yields in pA and AA reactions at a beam energy of 14.5 GeV [26] can be well reproduced by the RQMD calculations (compare fig. 15). In fig. 15 we have shown in addition K^+ and K^- production in $p+A$ reactions. If we compare $p+Be$ and $p+Au$ we see that the absolute strange hadron yields are enhanced in the latter case. This is a rather trivial effect in the RQMD calculations resulting mostly from subsequent baryon-baryon collisions. In central $Si+Au$ reactions a strong K^+ enhancement (factor of 2) and moderate K^- enhancement (25 %) relative to the pion yields is found from the RQMD calculations. The overall agreement for strange particles between RQMD and E802 data is surprisingly good, if one takes the complex reaction dynamics into

Figure 14: Sources of strange particle production in minimum bias reactions $p(200 \text{ GeV})$ on gold extracted from the RQMD calculations as a function of the final rapidity of the strange hadron. The sources for Λ 's are: baryon-baryon (BB) collisions (straight line), πN collisions (dashed line), $\bar{K}N$ collisions (dotted line), and other meson-baryon (MB) collisions (dashed-dotted line). The sources for $\bar{\Lambda}$'s are: BB collisions (straight line), MB collisions (dashed line), and rope fragmentation (dotted line). The sources for K 's are: BB collisions (straight line), MB collisions (dashed line), and rope fragmentation (dashed-dotted line). The sources for $\bar{K}$'s are: BB collisions (straight line), MB collisions (dashed line), and MM collisions (dashed dotted line).

Figure 15: Calculated and experimental meson rapidity distributions for minimum bias $p+Be$ (left), $p+Au$ (middle) and central $Si+Au$ (right) reactions at a projectile energy of 14.5 AGeV. The histograms represent the RQMD results: π^- (solid line), K^+ (dashed line) and K^- (dotted line). The experimental data are shown for π^- as circles, for K^+ as dots and for K^- as squares. The $Si+Au$ distributions are divided by 28. We have multiplied the E802 pion data for $Si+Au$ with 1.2, because the RQMD calculations show 20 % additional pions in the unmeasured low p_t region above a linear extrapolation in the transverse momentum spectra which was done by E802.

account.

From the RQMD calculations we infer that the baryon-baryon sector produces kaons with approximately the same suppression factor as in $p(14.5\text{GeV})p$. However, the meson-baryon interactions produce nearly the same number of kaons in addition. The basic reason for enriching strangeness in $Si+Au$ compared to pp and pA collisions is the interaction of resonant meson and baryon states. As stated above the resonant meson-baryon annihilation in the relevant energy region produces hyperons and kaons without a net effect on the pion yields. In RQMD there are about 90 meson-baryon annihilations above strangeness production threshold in $Si+Au$. The meson-baryon dominance of additional kaon production explains the strong rapidity dependence of the kaon rapidity distribution. The initially produced mesons are peaked at midrapidity, the second generation has rapidities nearer to the target due to the same asymmetry effect as in pA . Produced particles from meson-baryon interactions are shifted even more towards target rapidity. In contrast, a meson-meson based kaon production gives a much more symmetric kaon rapidity distribution in disagreement with the data. This is a strong argument against models in which the strangeness enhancement in $Si(14.5\text{AGeV})+Au$ is due to $\pi\pi$ annihilation [46]. In RQMD the meson-meson contribution is practically negligible if a realistic $\pi^+\pi^- \rightarrow K^+K^-$ cross section (here: 1.8 mb) above $\sqrt{s}=1$ GeV is used, but no strong coupling of other

meson pairs to $K\bar{K}$.

4.2 Colour rope formation and strange baryon pairs

A strong production of strange baryon-antibaryon pairs has been experimentally observed in the central region (midrapidity) of nucleus-nucleus reactions at 200 AGeV [36,47]. Several ideas have been proposed in the past for an explanation of this new baryon component: quark-gluon plasma formation [48], more body interactions [49], medium modifications of hadron masses [50] and the generation of strong chromoelectric fields (“ropes”) [19]. The rope mechanism has been implemented into relativistic quantum molecular dynamics (RQMD 1.08).

In fig. 16 we show the results of the RQMD calculations for central S(200AGeV) on S collisions *without* rope formation. Further on we did the calculation twice: with and without secondary rescattering. The corresponding rapidity distributions for neutral strange particles are shown together with the experimental measurements of the NA35 group. The RQMD calculations which include rescattering reasonably agree with the NA35 data for the protons and the total charged particle momentum distributions [15,51]. The model including primary collisions only completely fails to reproduce the observed strangeness enhancement (for K_S , Λ 's and $\bar{\Lambda}$'s).

In fig. 16 we also show RQMD calculations with hadronic rescattering included. The agreement for K_S and Λ 's improves noticeably. Binary hadronic rescattering thus provides the reaction rates to explain enhanced kaon and lambda yields which are reported by NA35 for central reactions S(200AGeV)+S, but *not* for the antilambda yields. Hadronic rescattering even decreases the total antibaryon yields, (compare full and dashed line histograms in fig. 16), because produced antibaryons may annihilate on surrounding baryons. The $\bar{\Lambda}$ enrichment due to rescattering and annihilation are balancing each other.

In fig. 17 we included rope formation and decay into the calculation. It turns out that the total charged particle distributions and the nucleon distributions (not shown) remain practically unchanged. Even the effect of rope decay on the kaons is pretty small. While the average strangeness suppression factor in the ropes is strongly enhanced (about 0.50), the absolute number of strange particles does not increase that strong, because the total multiplicities from rope decay are roughly 30 percent lower than in the independent string case. This is caused by the much faster decay of a rope compared to an elementary string which results in a smaller amount of created $q\bar{q}$ pairs. The effect of $s\bar{s}$ enhancement on kaon yields is diminished by the fact that an increasing fraction of s quarks goes into strange baryons (the $q\bar{q}$ suppression weakens more dramatically than s suppression) and into hidden strangeness (η and η').

We also conclude from fig. 17 that rope formation provides a mechanism for strong production of diquarks resulting in antibaryon enhancement. Fig. 17 shows a nice agreement between measured and calculated Λ yields. In addition, we present our pre-

S(200AGeV)+S

Figure 16: Comparison of strange particle yields in central S+ S collisions at a beam energy of 200 AGeV between RQMD 1.08 without ropes and NA35 data. The rapidity distribution for Λ 's, $\bar{\Lambda}$'s, and K_s is shown. The results of the calculation include the experimental transverse momentum cutoffs: $p_t = 0.5$ GeV for Λ 's and $\bar{\Lambda}$'s, $p_t = 0.62$ GeV for K_s . The histograms represent the calculated rapidity distributions including secondary rescattering (solid line) and primary collisions only (dashed line), the symbols the measurement. In addition the calculated antiproton distribution excluding those from Λ decay is shown.

S+S (string fusion included)

Figure 17: The same comparison as in fig. 16, but this time rope formation – in addition to secondary rescattering – is included into the RQMD calculation.

S(200 AGeV)+W

Figure 18: RQMD 1.08 calculation of central S(200 AGeV) + W collisions: The rapidity distribution for p , $\bar{p}$, Λ , $\bar{\Lambda}$, and K_S is shown. The calculated (anti-)proton distribution includes those from (anti-) $\bar{\Lambda}$ decay.

diction for the antiproton rapidity distribution. We infer from our calculations that there is a complicated interplay between additional diquark production mechanisms in ultrarelativistic heavy ion collisions and annihilation due to final state interactions with surrounding baryons. Half of the initially produced $\bar{p}$'s and $\bar{\Lambda}$'s are “eaten up” by this mechanism. A similar observation has already been made at lower beam energies [52]. If we compare the calculated antiproton yields – normalized on pions – with the corresponding ratio in pp collisions we conclude that the final antiprotons are enhanced by about 70 percent. This prediction can be tested in present experiments at CERN. Additional information on the dynamics can be extracted from nuclear collisions by measuring the *mass dependence* of baryon and antibaryon production. The *collective effects* like rope formation and antibaryon annihilation in the baryon dense system do not have the same projectile and target and rapidity dependence. Experimental data at different rapidity windows for different projectile-target combinations are therefore of utmost importance. In fig. 18 we present the RQMD 1.08 prediction for central S(200 AGeV) on W collisions. We infer from this calculation that the trend of enriching strange particles around midrapidity continues compared to S+S in fig. 17.

Our conclusion is that there is considerable evidence for a nonconventional diquark production mechanism in ultrarelativistic nucleus-nucleus collisions. Colour ropes with strong chromoelectric fields provide an explanation for the observed Λ enhancement in central S+S collisions. A nice feature of the colour rope model is that it leads to quite specific predictions for different observables. There is an intimate connection between hadron p_t distributions and strength of the chromoelectric field formed. Furtheron we expect that – at collider energies – the rope fields are sufficiently strong to create even *soft* $c\bar{c}$ pairs leading to open charm enhancement in RHIC experiments. It would be extremely important for a better understanding

of QCD if the existence of an exotic state like a colour rope can be experimentally proven.

5 Antibaryon annihilation

Antibaryons are sensitive to the baryon dynamics in heavy ion collisions because of their large annihilation probabilities in a baryonic medium [53]. If the initially produced yields and their formation time would be known the final yields could tell about the lifetime, extension and density of the baryon dense system created in nuclear collisions. However, as we have discussed before the initial production might be heavily influenced by nuclear and collective effects, e. g. the colour rope formation which dramatically enhances diquark pair creation rates.

A variation of the beam energy may help to disentangle the importance of the various effects, e. g. the annihilation effect is expected to be stronger at lower energies (more baryon stopping, higher $B\bar{B}$ annihilation cross sections) and – in contrast to rope formation and even string production should become suppressed. At the AGS heavy ion experiments spectra of antiprotons were measured by several groups [54,55] at an incident energy of 14.5 AGeV. In the following part we compare some of these experimental results with RQMD calculations to learn more about the collision dynamics.

As we have shown in [52] multi-step processes dominate the initial antibaryon yields in nuclear collisions at 14.5 AGeV. Around this energy the $\bar{p}$ yield in pp collisions is extremely energy dependent, because the production threshold is not too far away. Therefore it is often favorable in nuclear collisions that a projectile picks up the necessary energy to produce an antinucleon from the target in more than one collision. In RQMD this is described by exciting a baryon further and further until its invariant mass exceeds three baryon masses. This reaction mechanism completely invalidates the first chance collision model in which antinucleons are produced only in collisions between nucleons from the target and the projectile which have not collided yet. Note that these multi-step processes may be also relevant for the subthreshold antiproton production measured at SIS (GSI). The microscopic cascade in RQMD leads to more initially produced antiprotons – e.g. a factor 3-4 for Si + Al than expected from the production rate in first collisions only. On the other side the escape probability of a produced antibaryon is rather low at AGS energy. The survival rate is only about 15% in case of the Si + Au system. The cancellation of two large numbers – multi-step processes and annihilation – makes it impossible to extract directly information on the intermediate baryon dense system in heavy ion collisions as suggested by Gavin et al. [53].

The final p yield in RQMD depends strongly on the antibaryon formation time. This is demonstrated in fig. 19, which shows RQMD results for Si(14.5 AGeV) + Au with varying formation times. The RQMD default description is to define the forma-

Si(14.6 AGeV)+Au (central)

Figure 19: Antiproton rapidity distribution dn_p/dy for central Si(14.6 AGeV/c) + Au collisions as calculated with RQMD 1.07 for different formation times ($\tau = \infty, 6.5, 1.5$ fm/c) is compared to the data of the E802 group [54].

Figure 20: Initially produced (p_i), final (p_f) antiproton and π^- yields as a function of the participant number in $A(14.6\text{ AGeV}) + A$ collisions calculated with RQMD 1.07.

tion point of a hadron as the arithmetic mean of the two string break points from which the quarks emerge which built up a hadron. This gives an average formation time $\tau = 1.5 \text{ fm}/c$ for antibaryons in Si+Au. Note, however, that in the string fragmentation scheme the break points are calculated as if the produced quarks were *massless*. This is certainly not true for diquarks which have a constituent quark mass around $700 \text{ MeV}/c^2$. The additional time needed to form a constituent (anti-)diquark may therefore be estimated to be around $0.7 \text{ fm}/c$ (assuming a string tension $\kappa = 1 \text{ GeV}/\text{fm}$). A larger formation time leads to a dramatic rise in the antiproton survival rate as can be seen in fig. 19. A slightly higher formation time than the RQMD default values seems to be in good agreement with the experimental data of the E802 group [54] which are also shown in fig. 19.

It is necessary to study systematically antibaryon production with various projectile-target combinations to eventually disentangle the various nuclear effects [56]. Fig. 20 shows the fully integrated ratios $\bar{p}/\pi^-$ for different A+A reactions. It seems that one has to go to very heavy projectile-target combinations (like Au+Au) until the annihilation induced loss of antinucleons wins over the multi-step contributions to antiprotons. We have to await future antiproton measurements for these systems to make further progress in understanding the antinucleon dynamics in a baryon dense medium at 10 to 15 AGeV.

6 Dilepton emission

Penetrating probes are an unique tool to investigate the properties of a medium which is otherwise inaccessible. An example is the measurement of neutrinos emitted from the sun. For the study of dense matter created in the intermediate stage of nuclear collisions it has been suggested that photons and dileptons might be such a useful probe, because they are interacting only electromagnetically with the surrounding medium. One of the exciting possibilities of dilepton measurements is the study of hadrons propagating in a dense medium. Quark models (NJL type) and QCD sum rule inspired approaches predict huge effects of high baryon densities, e. g. a mass shift of the ρ meson.

Dielectron production in proton and heavy ion induced reactions at medium incident beam energies has been measured by the DLS-collaboration at the Bevalac [57,58]. The DLS data have been compared to various reaction models [59,60,61,62,63]. The experiments at $E_{kin} = 1 \text{ AGeV}$ for light systems like p+Be and Ca+Ca can be explained by pn bremsstrahlung, Δ Dalitz decays and $\pi^+\pi^-$ annihilation [63]. At $E_{kin} = 4.96 \text{ GeV}$, the highest available energy at the BEVALAC, efforts have been made to explain the DLS-data for p+Be by pn bremsstrahlung [59] or by $\pi^+\pi^-$ annihilation [60]. Previous parametrisations of pn bremsstrahlung [59] overestimate the data at this energy, especially above dielectron masses of $M = 1 \text{ GeV}/c^2$.

Figure 21: The differential cross section for dielectron production for Au + Au at 10.6 AGeV incident kinetic energy versus invariant mass of the dielectron. The dotted line refers to Dalitz decays (most prominent source is the η -Dalitz decay), the dashed line to vector meson decays (ρ^0/ω , and the dashed-dotted line to pn bremsstrahlung. The pion annihilation component of the ρ meson decay and the contribution from decays of ω 's are shown separately. The solid line represents the sum of all contributions.

sources of dileptons in p+A and A+A collisions. Dalitz decays of the Δ_{1232} are included as well as N_{1520}^* , η , ω , η' . The differential decay rates depend on the invariant mass of the dielectron and on the actual mass of the decaying particle. Vector mesons such as ρ^0 and ω can convert into a dilepton pair. pn bremsstrahlung is calculated in the soft photon approximation based on a parametrization of the measured pn differential elastic cross section. However, the strong forward peak of elastic scattering at energies of several GeV suppresses its contribution to heavy mass dileptons. It has been shown in [64] that this model describes rather well both the mass and the p_t distributions of the data for light systems [57,58]. Decays of η 's, Δ 's, ρ 's and ω 's dominate the dielectron mass spectra above the π^0 -mass. The prediction made there for p + p and p + d is consistent with recent observations of the DLS-collaboration: the number of dielectron pairs in p + p constitute approximately one half of the dielectron yield in the reaction p + d [57], disapproving a prominent role of pn bremsstrahlung.

Up to now we did not include medium modified "effective" meson masses, but use always the free meson properties. The BEVALAC energy region is probably

influence on hadron properties. Therefore it is worthwhile to study dilepton production in the AGS beam energy region (10-15 AGeV). Fig. 21 shows the differential dielectron cross sections versus invariant dielectron mass for Au + Au at 10.6 AGeV incident kinetic energy. The yields below $M \sim 500 \text{ MeV}$ are dominated by the Dalitz decays of the η . For higher masses a large contribution of ρ/ω decays from resonance formation is predicted from our calculation. The pn bremsstrahlung component is suppressed by more than two orders of magnitude as compared to contributions from Dalitz decays. This suggests that bremsstrahlung from inelastic reactions or meson-meson and meson-baryons collisions is reduced as well, but the quantitative analysis has not been done yet.

However, due to the higher energy as compared to dielectron measurement at the Bevalac the mass slope is much harder i.e. there is a clear separation between the Dalitz decays from the η 's and the decays from vector mesons. Therefore the ρ/ω peak should be clearly measurable in a dielectron experiment at AGS energies. A measurement of the modification of the ρ mass and decay – eventually even an ω/ρ mass splitting – considerably constrains currently available low energy approximations to QCD and would serve as a probe of the vacuum quark condensate at finite baryon density.

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