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Probing string fragmentation in nuclear matter: lepton-nucleus scattering

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ABSTRACT

We introduce a new model for the fragmentation of strings in a "medium" of hadronic objects. These objects may be hadrons, resonances, or string pieces from the fragmentation of other strings. As a first application we treat the fragmentation of a string inside a nuclear medium, taking into account interactions of the fragmenting string with spectator nucleons (spectators of the hard process which created the string in the first place). We compare with neutrino-neon data.

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1. Introduction

According to the parton model, a high energy lepton interacts with a nucleon as follows: via boson exchange a considerable amount of momentum is transferred to one of the quarks of the nucleon. The latter one is henceforth transformed into an object consisting of a quark and a diquark with a large relative momentum: a string (see fig. 1). Therefore lepton-nucleon scattering allows us to study the fragmentation of diquark-quark ($qq-q$) strings in vacuum.

For lepton-nucleus scattering the initial part of the interaction is like discussed above: due to the very small cross section the lepton will interact with just one nucleon, by transferring momentum to a quark, resulting in a quark-diquark string (see fig. 2). But since the string has been formed somewhere inside the nucleus, the space-time evolution of the string will be different from the vacuum case. The whole string or later string fragments may interact with spectator nucleons. So lepton-nucleus scattering provides the unique opportunity to study space-time evolution of strings inside a nuclear medium. This is not only interesting by itself, but also serves as a first step to understand much more complicated reactions like hadron-nucleus or nucleus-nucleus collisions, where many strings interact among each other and with spectators. Lepton-nucleus scattering therefore also provides a stringent test for models, designed to treat final state interactions in nucleus-nucleus collisions.

It is the purpose of this paper to present and study a model for a string fragmenting in a "medium". The medium consists of hadronic objects, like fragments from other strings or simply nucleons. We describe the model quite generally, although in this paper we only apply it for a nuclear medium, to investigate lepton-nucleon scattering. The fragmentation model is an ingredient of VENUS 3 – a string model for hadronic collisions – and is therefore sometimes referred to as VENUS 3 as well.

Let us briefly discuss the main ideas behind the model. At the formation point the string is very short, most of the string energy being concentrated at the endpoints. Given this initial condition the string will – according to the classical evolution equations – become eventually very long. However this does not really happen, since the string is going to break after a typical time of $1 \text{ fm}/c$. This means that the length of a string segment will in general not exceed 1 fm , which is of the order of a nucleon size. Therefore concerning reinteraction of string segments among each other and with spectator nucleons, we consider all these objects as pointlike. Thus we have just trajectories of string segments (rather than surfaces) and define to have an interaction whenever two trajectories come closer than a certain distance r_0 . How do we realize an interaction? Whereas string flip is the dominant mechanism at high energies, low energy scattering occurs predominantly via fusion. We therefore assume that reinteraction of segments occurs exclusively via fusion, the fused object decaying again after the appropriate time (if it does not interact before).

Although this is a rather crude model, it has obvious advantages. The first is its simplicity and transparency. Secondly it avoids parametrizing hundreds of cross sections which mostly are not well known, and it can handle collisions involving unstable particles. It is also not clear whether the vacuum cross section makes any sense in the nuclear medium anyhow. We put all these unknowns into one interaction radius r_0 ! We claim to provide

Fig. 1. Lepton-nucleon scattering in the Parton Model: the intermediate boson B transfers momentum to a quark, thus forming a quark-diquark string.

Fig. 2. In lepton-nucleus scattering a string is formed inside the nucleus. The kicked-off quark moves forward, the diquark is close (in momentum) to the spectator nucleons.

a zeroth-order model, which is adequate to investigate gross features of interacting string fragmentation.

In chapter 2 we are going to repeat briefly the vacuum fragmentation model, in chapter 3 we introduce the model for the fragmentation of strings in a medium (interacting strings), in chapter 4 we discuss neutrino nucleus scattering, and in chapter 5 we apply our model to calculate particle production in neutrino-neon scattering, and compare with data.

2. String fragmentation in vacuum

The vacuum fragmentation model has been discussed in great detail elsewhere [1], we are going to repeat the main features in this chapter. We consider a string to be a one-dimensional object evolving with time, thus defining a two-dimensional surface in space-time

$$x = x(\tau, \sigma) \quad (1)$$

with a spacelike parameter σ and a timelike one τ . The space-time evolution is determined by the action

$$S = -\kappa \int d^2A \quad (2)$$

being proportional to the surface area A swept by the string. This action can be derived from very plausible invariance requirements (see [1]). A solution of the equations of motion is (with $t = \tau$)

$$\vec{x}(t, \sigma) = \frac{1}{2}[\vec{y}(t + \sigma) + \vec{y}(t - \sigma)] \quad (3)$$

where $\vec{y}$ is obviously the trajectory of one endpoint $\vec{y}(t) = \vec{x}(t, 0)$, called directrix. The directrix has to be periodic

$$\vec{y}(t + 2\pi) - \vec{y}(t) = \frac{2\vec{P}}{\kappa} \quad (4)$$

Apart from this condition the directrix is arbitrary; strings can be classified according to properties of their directrices. The simplest case is a one-dimensional directrix, one period of which consisting of two linear segments (in space-time), see fig. 3 (yo-yo strings). From eq. (3) we can construct the trajectory of the other endpoint $\vec{x}(t, \pi)$, which we call antidirectrix, and also the whole string, which is just a straight line between directrix and antidirectrix. The endpoints can absorb and emit energy and momentum at a rate κdt . One can even show that such a yo-yo string is completely equivalent to two partons with a linear potential in between (see [1]). One can show that the momenta of the endpoints (p_q and $p_{\bar{q}}$) are related to (anti)directrix segments via

$$p_q^+(O) = \kappa \|OA\|; \quad p_{\bar{q}}^-(O) = \kappa \|OB\| \quad (5)$$

with $p^\pm(O)$ being the momenta of the endpoints ("parton" momenta) at O and with the definition of distance as $\|[(t, z)]\| = |t| + |z|$. So we have a mapping from "momentum space" to "real space" via

$$\Delta p = \kappa \Delta x. \quad (6)$$

with the string tension κ .

Fig. 3. Space-time picture of a "yo-yo" string with period $2P/\kappa$.

Fig. 4. Breaking of a "yo-yo" string. We indicate the relation between (anti-)directrix segments and parton momenta. In the string model the energy discontinuities (at the endpoints in the case of a yo-yo) can be identified with partons!

We are now going to discuss string breaking. Provided we know the space-time point of breaking, we know how to construct the new directrices and thus the new strings. Since for future, present, and past the laws of classical string dynamics apply, the prescription is as follows: determine the directrix segment which corresponds to the one string segment and the antirectrix piece corresponding to the other string segment (at the breaking time). Then periodically continue both directrices, which allows the construction of both strings for all the future. For yo-yo's this construction becomes extremely simple. In fig. 4, OAC and OB represent a half period of directrix and antirectrix of the original string (such an "elementary cell" $OABC$ defines the string completely). A break may occur at D . Due to the identities

$$\|AE\| = \|EG\|; \quad \|DE\| = \|EF\|$$

and

$$\|DI\| = \|IJ\|; \quad \|BI\| = \|IK\|$$

one can easily construct the new strings after breaking: $DEFH \dots$ and $AEGH \dots$ are directrix and antirectrix of one subtring, $DIJL \dots$ and $BIKL \dots$ of the other. Also in fig. 4 we relate (anti)directrix segments and "parton" momenta. For the initial "parton" momenta p_0^+ and p_0^- we get

$$\|OA\| = \frac{p_0^+}{\kappa}; \quad \|OB\| = \frac{p_0^-}{\kappa}. \quad (7)$$

We define "breakup momenta" $b_0^\pm$ via

$$\|OU\| = \frac{b_0^+}{\kappa}; \quad \|OV\| = \frac{b_0^-}{\kappa}. \quad (8)$$

Similar to eq. (7) we find for the "parton" momenta $p_1^\pm$ of the right subtring

$$\|EF\| = \frac{p_1^+}{\kappa}; \quad \|EG\| = \frac{p_1^-}{\kappa}. \quad (9)$$

The question where – in real space – the string breaks, is therefore closely related to the question of how the subtring momenta $p_1^\pm$ relate to the original string momenta $p_0^\pm$. Before writing down the breaking law, we introduce the two variables A (or $\mathcal{A}$) and η describing the position of the breakpoint D : the area A of absolute past with respect to the break point D is given as

$$A \equiv \frac{1}{\kappa^2} \mathcal{A} = \frac{1}{\kappa^2} b_0^+ b_0^-, \quad (10)$$

the space-time rapidity η is defined as

$$\eta = \frac{1}{2} \ln \frac{\|OU\|}{\|OV\|} = \frac{1}{2} \ln \frac{b_1^+}{b_1^-}. \quad (11)$$

Using the same invariance arguments which led to the action eq. (2) being proportional to the string surface, we obtain the result that the probability dP for a string to break within a certain surface element d^2A is proportional to d^2A , which leads to

$$dP(\mathcal{A}) = \alpha_0 e^{-\alpha_0 \mathcal{A}} d\mathcal{A} \quad (12)$$

with the "break probability" α_0 as a parameter. We use for the other variable η a flat distribution between the limits η^- and η^+ with

$$\eta_+ = \ln \frac{\sqrt{\mathcal{A}} p_0^+}{\mu_+^2 \min + \mathcal{A}}, \quad \eta_- = \ln \frac{\mu_-^2 \min + \mathcal{A}}{\sqrt{\mathcal{A}} p_0^-}, \quad (13)$$

where $\mu_{\pm \min}$ are the minimum possible transverse masses of the right and the left subtring. The mass spectrum of subtrings is continuous. As a unique feature of our model we leave this continuous spectrum, even if a subtring is a resonance. A ρ -meson for example is not forced to have 770 MeV, if it happens to be formed with, say, 700 MeV. The only exceptions are stable hadrons; here (and only here) we apply a correction procedure to guarantee on-shellness (see [1]). In this way we reduce correction procedures to a minimum, and if necessary, like for stable hadrons, the correction is really a small correction: we are looking for a new breakpoint D very close to the original one. So we disturb the fundamental string decay law eq. (12) as little as possible.

String pieces are identified with resonances, which then decay – after the appropriate lifetime – according to standard decay tables. We use a very elaborate resonance table, including for example all nucleon resonances up to 2 GeV (see [2]).

3. String fragmentation in a medium

We are now considering the fragmentation of a string in a medium of pointlike hadronic objects. These objects may be nucleons in a nucleus or string segments from the fragmentation of other strings. We first fragment a string S_0 according to the vacuum fragmentation procedure described in the last chapter, see fig. 5. The polygons $O_0 R_0 U_0$ and $O_0 L_0 U_0$ are a half period of directrix and antirectrix ("elementary cell"). The breakpoint B_0 defines the elementary cells $O_1 R_0 U_1 B_0$ and $O_2 B_0 U_2 L_0$ for the two subtrings S_1 and S_2 . Any further breaks have to occur inside these cells since the absolute past of B_0 (inside of $O_0 O_1 B_0 O_2$) is excluded from further breaks, otherwise B_0 would not be possible! The absolute future (inside of $B_0 U_1 U_0 U_2$) is of course also excluded. In the next step, the subtrings S_1 and S_2 take the role of the original one. The breakpoints B_1 and B_2 (see fig. 5(b)) determine the string decays $S_1 \rightarrow S_{11} + S_{12}$ and $S_2 \rightarrow S_{21} + S_{22}$. The procedure is continued till all subtrings S_α have a mass smaller than some cut-off.

From the example in fig. 5 it becomes clear that the sequence of breakpoints is in general not time-ordered in a certain Lorentz frame: the second-generation breakpoint B_1 happens to be earlier than the first-generation break at B_0 . This is a consequence of our covariant fragmentation scheme. At this point we want to give up covariance and choose

Fig. 5. Consecutive string breaking: the first break occurs at B_0 (a), the substrings then break at B_1 and B_2 (b). In this example the second break at B_1 occurs in our reference system earlier than the first break at B_0 . In (c) we reconstruct time ordered decays.

an appropriate Lorentz frame. In this frame we determine the real time sequence of string breakups:

$$(B_{\alpha_1})_0 < (B_{\alpha_2})_0 < (B_{\alpha_3})_0 < \dots, \quad (14)$$

where the index zero ($_0$) indicates the time component. In fig. 5 we have for example $(B_1)_0 < (B_0)_0 < (B_2)_0$. Keeping the sequence eq. (14), we check at these times $(B_{\alpha_i})_0$ whether a break between two consecutive string segments occurred later; if so, the break is considered (at this time) not existent and the two string pieces are joined again. In this way we obtain a time-ordered decay, the first break occurring at $t = (B_{\alpha_1})_0$:

$$S_0 \rightarrow \tilde{S}_1 + \tilde{S}_2 \quad (15)$$

the next one at $t = (B_{\alpha_2})_0$, depending whether $\tilde{S}_1$ or $\tilde{S}_2$ decays next as

$$\tilde{S}_1 \rightarrow \tilde{S}_{11} + \tilde{S}_{12} \quad \text{or} \quad \tilde{S}_2 \rightarrow \tilde{S}_{21} + \tilde{S}_{22} \quad (16)$$

and so on. In the example of fig. 5 we have at $t = (B_1)_0$

$$S_0 \rightarrow \tilde{S}_1 + \tilde{S}_2 \equiv S_{11} + \{S_{12} + S_{21} + S_{22}\} \quad (17)$$

then at $t = (B_0)_0$

$$\tilde{S}_2 \equiv \{S_{12} + S_{21} + S_{22}\} \rightarrow \tilde{S}_{21} + \tilde{S}_{22} \equiv S_{12} + \{S_{21} + S_{22}\} \quad (18)$$

and finally at $t = (B_2)_0$

$$\tilde{S}_{22} \equiv \{S_{21} + S_{22}\} \rightarrow \tilde{S}_{221} + \tilde{S}_{222} \equiv S_{21} + S_{22}. \quad (19)$$

We construct geometrically, as shown in fig. 5(c), the "origins" $\tilde{O}_\alpha$ for the string segments $\tilde{S}_\alpha$. Since we keep track of all parton momenta, we can easily determine the momenta $\tilde{p}_\alpha$ of the string segments. We define a track of a segment to be a straight line, going through the origin, with the direction given by the velocity of the segment:

$$(x_\alpha(t))_i = (\tilde{O}_\alpha)_i + \frac{(\tilde{p}_\alpha)_i}{(\tilde{p}_\alpha)_0} [t - (\tilde{O}_\alpha)_0] \quad (20)$$

with $i = 1, 2, 3$ being the space components, $t = 0$ being the time component. This track corresponds approximately to the diagonal $\tilde{O}_\alpha \tilde{U}_\alpha$ of the elementary cell, only approximately because of the transverse momenta involved, which are however small. We have to consider of course that the string segment $\tilde{S}_\alpha$ lives on this line only for a time interval $t_\alpha^1 < t < t_\alpha^2$, limited by the breaktime t_α^1 where this segment occurred first, and the breaktime t_α^2 where $\tilde{S}_\alpha$ further decays. The actual track

$$\{(x_\alpha(t))_i; t_\alpha^1 < t < t_\alpha^2\} \quad (21)$$

in general does not contain the origin $\tilde{O}_\alpha$.

So we have the following situation: between the time $(O_0)_0$ where the string was formed and the time $(B_{\alpha})_0$ of the first break, we have just one track, the track $\tilde{x}_0(t)$ of the whole string. After the first break till the next one at $(B_{\alpha})_0$ we have two tracks corresponding to the two substrings $\tilde{S}_1$ and $\tilde{S}_2$, and so on. The final string segments have no upper limits (so far, till we consider resonance decay), they follow their track till $t = \infty$.

As the next step we have to consider resonance decay, which in general also limits the lifetime of the final string segments. Knowing the mass and quark content of a segment, we identify it with a resonance according to our resonance table (a detailed description of this procedure is given in [2]). Also from the table we obtain the lifetime τ_R of the resonance R , which therefore lives on the straight line trajectory between the formation time t_R and $t_R + \gamma\tau_R$, with the Lorentz dilation factor γ . At the latter time we decay the resonance according to a standard decay table (see [2]), thus at that point the resonance track bifurcates into two (or more) daughter tracks and so on.

We have thus a complete space-time evolution of the string and its decay products from the string formation time till infinity. This is an improvement over earlier space-time studies [3], where we only considered resonances, but not, however, their "parent" string segments. So in a way particles were created at some stage from "nothing", whereas now we keep track of energy and momentum from the beginning till the end.

All this exercise of constructing time-ordered string decays is only necessary if we consider interactions at an early stage, before the last breakup. For interactions of segments it is obviously important which event happens earlier than some other event (we mean events of two segments coming close to each other and interacting). We are now considering how string fragmentation as described above is modified in a medium of pointlike hadronic objects H_β , the latter ones moving on tracks $\tilde{x}_\beta(t)$. Whenever at some time t such a track comes close to the track $\tilde{x}_\alpha(t)$ of a string segment $\tilde{S}_\alpha$, i.e.

$$|\tilde{x}_\alpha(t) - \tilde{x}_\beta(t)| \leq r_0, \quad (22)$$

then these two objects interact. The two are most likely close in momentum space (for cases we want to apply this model: lepton-nucleus or nucleus-nucleus scattering), so for simplicity we assume all interactions to result in fusion of the two objects:

$$\tilde{S}_\alpha + H_\beta \rightarrow R \quad (23)$$

where the quark content and momenta of R are just the sums of these quantities of the two ingredients. According to its mass and quark content this object R is identified with the help of a resonance table its lifetime τ_R is determined, and after the time interval $\gamma\tau_R$ this object R decays again into resonances or hadrons:

$$R \rightarrow R_1 + R_2 + \dots \quad (24)$$

In fact we perform this procedure of checking the distance and fusing (if necessary) for all string segments, decay products, "medium" particles, results of fusions (eq. (23)), or decay products of such fused objects (eq. (24)), so we include all particles present at a

certain time. Of course if a segment $\tilde{S}_\alpha$ is involved in an interaction eq. (23) at a time t , all the decay products of $\tilde{S}_\alpha$, which would otherwise occur later, are not existent! Technically speaking, all the breaks of the vacuum string are first done, even if some of them later turn out to be irrelevant, due to a fusion process eq. (23) of some parent string segment.

Theoretically there is the possibility that string segments from one single string reinteract and fuse; however, this happens so rarely that this process is irrelevant. The dominant reinteraction process for string fragmentation in a nucleus (lepton-nucleus scattering) is the following: low mass mesons from string decay, which are close in momentum space to the spectator nucleons, interact with these nucleons, fuse into moderately excited resonances, and decay again into a baryon and one or two mesons, the baryon being slow in the nuclear rest frame. In this way the multiplicity is not drastically increased, apart from the additional baryons, which without interactions would remain spectators.

4. Parton model of neutrino-nucleus scattering

This chapter provides the link between string fragmentation in a nucleus – for which we constructed a model – and lepton-nucleus scattering – where data exist. Let us first consider lepton-nucleus scattering (see fig. 1). We use the following variables: $k \equiv (k_0, \vec{k})$ and $k' \equiv (k'_0, \vec{k}')$ are the momenta of incoming and outgoing lepton, $q \equiv k - k'$ is the momentum of the exchanged boson, we use as usual $Q^2 \equiv -q^2$ for the virtual mass of the boson, θ and ϕ are the polar and azimuthal angles of the scattered lepton relative to the beam axis in the nucleon rest frame and W^2 is the square of the "string mass", i.e. the mass of "boson + nucleon". For the experiment which we are going to consider [4] we know average values for k_0 , Q^2 , and W^2 . From momentum conservation at the boson-nucleon vertex we have (with m_N being the nucleon mass)

$$-Q^2 + m_N^2 + 2m_N(k_0 - k'_0) = W^2 \quad (25)$$

from which we obtain the energy k'_0 of the scattered lepton. In the nucleon rest frame we have

$$q = \begin{pmatrix} k_0 - k'_0 \\ -k'_0 \sin \theta \sin \phi \\ -k'_0 \sin \theta \cos \phi \\ k_0 - k'_0 \cos \theta \end{pmatrix} \quad (26)$$

with θ to be obtained from

$$Q^2 = 2k_0 k'_0 (1 - \cos \theta). \quad (27)$$

The string momentum p is the sum of the boson and nucleon momentum, so in the nucleon rest system we have

$$p = q + (m_N, 0, 0). \quad (28)$$

We use the string cm system as reference system where the fragmentation procedure as described in the last chapter is being performed. We boost the target nucleus into this

system via

$$x'_0 = \beta_0 x_0 + \sum_{i=1}^3 \beta_i x_i \quad (29)$$

$$x'_j = \beta_j x_0 + x_j + \frac{\beta_j}{1 + \beta_0} \sum_{i=1}^3 \beta_i x_i \quad (30)$$

with

$$\beta_\mu = \frac{p_\mu}{\sqrt{p^2}}, \quad \mu = 0, 1, 2, 3$$

being the string velocity.

To provide some numbers: for the neutrino-neon experiment with which we want to compare [4], we have an incident neutrino energy of 43 GeV, a momentum transfer Q^2 of 5.4 GeV² and a string mass squared W^2 of 27 GeV². From eq. (25) we obtain an energy transfer $q_0 = k_0 - k'_0$ of 16.76 GeV and the scattering angle from eq. (27) turns out to be 3.96°. So the W-boson moves with almost half of the incident neutrino energy almost in beam (=forward) direction. Since this momentum is transferred to one quark of the hit nucleon (see fig. 1), this quark consequently moves with a large momentum forward (see fig. 2). After the Lorentz boost eq. (29), in the string frame, the nucleons move almost along the string axis in backward direction (in the diquark direction). We expect therefore rescattering effects in the backward region (diquark fragmentation region). This will be investigated in the next chapter.

Finally we have to specify the flavour content of strings in charged current neutrino-nucleus scattering. Using the variables

$$x_B \equiv \frac{Q^2}{2m_N(k_0 - k'_0)}, \quad y \equiv \frac{k_0 - k'_0}{k_0}, \quad (31)$$

the probability $P(q_\alpha \rightarrow q_\beta)$ for a certain current $\langle q_\beta | J | q_\alpha \rangle$ is, if q_α and q_β are quarks, given as

$$P(q_\alpha \rightarrow q_\beta) = N c(q_\alpha \rightarrow q_\beta) \int dx_B dy \frac{G^2}{\pi} s_{x_B} q_\alpha(x_B), \quad (32)$$

for antiquarks q_α and q_β as

$$P(q_\alpha \rightarrow q_\beta) = N c(q_\alpha \rightarrow q_\beta) \int dx_B dy \frac{G^2}{\pi} s_{x_B} (1 - y)^2 q_\alpha(x_B), \quad (33)$$

where N is a normalization constant, $q_\alpha(x)$ are the (anti)quark momentum distribution functions, and $c(q_\alpha \rightarrow q_\beta)$ represents Cabibbo mixing, the non-zero coefficients being

$$c(q_\alpha \rightarrow q_\beta) = \begin{cases} \cos^2 \theta_C & \text{for } d \rightarrow u, \bar{u} \rightarrow \bar{d} \\ \sin^2 \theta_C & \text{for } d \rightarrow c, \bar{c} \rightarrow \bar{d} \\ \sin^2 \theta_C & \text{for } s \rightarrow u, \bar{u} \rightarrow \bar{s} \\ \cos^2 \theta_C & \text{for } s \rightarrow c, \bar{c} \rightarrow \bar{s} \end{cases} \quad (34)$$

with the Cabibbo angle θ_C . To each current $q_\alpha \rightarrow q_\beta$ there corresponds a string with q_β and $(N_0 - q_\alpha)$ at the ends, where N_0 is the nucleon involved. So for example a current $d \rightarrow u$ in neutrino-proton scattering provides a $u - uu$ string. Since there are no $\bar{c}$ quarks in a nucleon, only six of the eight possibilities of eq. (34) are realized. The numerical values for the corresponding weights, calculated according to eqs. (32,33,34), taking equal probability for neutron and proton targets (symmetric nuclei), are given in table 1.

current	p-string	P[%]	n-string	P[%]
$d \rightarrow u$	$u - uu$	27.37	$u - ud$	58.21
$\bar{d} \rightarrow c$	$c - uu$	1.44	$c - ud$	3.06
$s \rightarrow u$	$u - \bar{s}ud$	0.13	$u - \bar{s}udd$	0.15
$s \rightarrow c$	$c - \bar{s}ud$	2.43	$c - \bar{s}udd$	2.88
$\bar{u} \rightarrow \bar{d}$	$\bar{d} - uud$	1.88	$\bar{d} - uudd$	2.23
$\bar{u} \rightarrow \bar{s}$	$\bar{s} - uud$	0.10	$\bar{s} - uudd$	0.12

Table 1: The weights of individual string contributions for the ν -Ne reactions discussed in the paper. $p(n)$ -string refers to a proton(neutron) being the target.

For qualitative arguments later we note that we have more than 50 % $ud - u$ strings, and more than 25 % $uu - u$ strings; everything else has small weight.

5. Results

In this chapter we study inclusive particle spectra for neutrino-neon scattering. Since our fragmentation model is part of the more general string model VENUS 3 for hadronic scattering, we refer to all calculations as VENUS 3. We generate strings with mass 4.5 GeV according to table 1, to compare with the data of [4]. Rescattering effects are essentially only affected by one parameter: the interaction radius r_0 (see eq. (22)). In the following we are comparing two scenarios:

$$\begin{aligned} r_0 = 0 & \quad \longleftrightarrow \quad \text{interaction turned off} \\ r_0 = 0.7 \text{ fm} & \quad \longleftrightarrow \quad \text{best guess for interaction radius} \end{aligned}$$

where our default value of $r_0 = 0.7$ fm may not be the final answer, due to the limited amount of data analyzed. In the following figures we shall use dashed lines if using $r_0 = 0$ and solid lines if using $r_0 = 0.7$ fm (default value in VENUS 3.00).

We first consider distributions of the longitudinal momentum fraction $x = p_i/p_i^{\text{max}}$, where p_i is the longitudinal momentum of a produced particle in the string frame and p_i^{max} is the maximum possible momentum. Positive x is defined to be the direction of the (anti)quark kicked off by the intermediate boson, negative x is the direction of the remainder, which is most likely a diquark (see table 1). As discussed in the last chapter,

the target spectator nucleons reside (in momentum) close to the "diquark", therefore we expect effects at $x < 0$.

In figs. 6 and 7 we display x -distributions of pions with (solid) and without (dashed) final state interactions. Let us first discuss the π^- distribution. For $x > 0$ we see almost no difference between the solid and dashed histogram, there is no rescattering effect - as we expected - since $x > 0$ corresponds to the forward side of the string, where the fragmentation occurs outside the nucleus. However, since the diquark end of the string fragments well inside the nucleus, we see a huge effect for $x < 0$: in the tails the two histograms differ by one order of magnitude. So there are considerably more π^- produced in the diquark fragmentation region, if rescattering is considered. The overall multiplicity however changes only slightly, since this quantity is dominated by the production in the central region, around $x = 0$ (note the logarithmic scale in fig. 6). The VENUS results with interaction reproduce the π^- data over the full x range. Concerning the π^+ distributions (fig. 7) the situation is quite similar: taking into account final state interactions considerably improves the agreement between calculation and data. However there still seem to be considerably more particles in the data. Since this excess is also observed for $x \geq 0$, it cannot be due to a wrong interaction model. Because we can easily reproduce lepton-nucleon data from other experiments (see [1]), which seems to support our vacuum fragmentation model, we are tempted to blame particle misidentification for the difference.

In figs. 8 and 9 we investigate strange particle production. Also for kaons (K_s) we observe something similar as for pions: rescattering has no effect in forward direction, but increases particle production in the backward tails. However the latter effect is smaller than for pions. Also for the lambdas (fig. 9) we observe an increase in the backward tails. The disagreement at forward x can probably be cured by an appropriate dependence of the diquark production rate on the available phase space. This is still under investigation.

In figs. 10 to 13 we show rapidity distributions corresponding to the x -distributions discussed above. We observe the same features as discussed before: a satisfactory improvement in the backward hemisphere by considering final state interactions, a smaller effect for kaons than for pions, an excess of π^+ in the data, however less measured than calculated Λ particles in the forward direction.

In figs. 14 and 15 we compare transverse momentum distributions. The solid and dashed histograms almost agree, there is almost no effect of rescattering. The histograms provide a reasonable fit to the data. The experimental kaon distribution is however flatter in the tails than the calculations.

Fig. 6. Longitudinal momentum distributions of negative pions in ν -Ne scattering. The points are data, the solid histograms are VENUS results with final state interactions ($\tau_0 = 0.7$ fm), for the dashed ones interactions are turned off ($\tau_0 = 0$).

Fig. 7. Longitudinal momentum distributions of positive pions in ν -Ne scattering. Same conventions as in fig 6.

Fig. 8. Longitudinal momentum distributions of kaons (K_s) in ν -Ne scattering. Same conventions as in fig 6.

Fig. 9. Longitudinal momentum distributions of lambdas in ν -Ne scattering. Same conventions as in fig 6.

Fig. 10. Rapidity distributions of negative pions in ν -Ne scattering. The points are data, the solid histograms are VENUS results with final state interactions ($r_0 = 0.7$ fm), for the dashed ones interactions are turned off ($r_0 = 0$).

Fig. 11. Rapidity distributions of positive pions in ν -Ne scattering. Same conventions as in fig 10.

Fig. 12. Rapidity distributions of kaons (K_s) in ν -Ne scattering. Same conventions as in fig 10.

Fig. 13. Rapidity distributions of lambdas in ν -Ne scattering. Same conventions as in fig 10.

Fig. 14. Transverse momentum distributions of kaons (K_s) in ν -Ne scattering. The points are data, the solid histograms are VENUS results with final state interactions ($r_0 = 0.7$ fm), for the dashed ones interactions are turned off ($r_0 = 0$).

Fig. 15. Transverse momentum distributions of lambdas in ν -Ne scattering. Same conventions as in fig 14.

6. Conclusion

We have proposed a very simple and transparent model for string fragmentation in a medium of hadronic objects. We propose as interaction mechanism fusion of a string fragment with one of these objects, whenever they come closer than an interaction radius r_0 . Although this is essentially the only parameter which affects rescattering, we can nicely reproduce many distributions in neutrino-neon scattering, which mainly probes the fragmentation of a diquark-quark string inside a nucleus. We clearly observe rescattering effects in the backward hemisphere: there is considerably more particle production in the backward tails of the distributions, whereas the overall multiplicity is only slightly increased. This result is important for understanding the dynamics of much more complicated processes like hadron-nucleus or even nucleus-nucleus collisions [5].

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