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QUARK DYNAMICS IN SOFT HADRONIC COLLISIONS
AND FRAGMENTATION ON NUCLEAR TARGETS

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ABSTRACT

Additive and collective pictures of quark dynamics in hadron-hadron collisions lead to different predictions for attenuation effects on nuclear targets and can be distinguished experimentally.

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It has been realized for some time that hadron-nucleus collisions provide a good laboratory for studying hadron-hadron interactions¹⁾. In this letter we show that collisions on nuclei provide the unique possibility (not available in hadron-hadron collisions) to reveal certain aspects of the role played by the quark structure of hadrons in soft hadronic collisions. More precisely, we expect that studies of the projectile fragmentation in hadron-nucleus collisions will allow to distinguish between, what we shall call and explain below, additive versus collective behaviour of quarks in hadron-hadron collisions. Taking the quark structure of hadrons as well established we believe that the above-mentioned alternative stands as a fundamental question for the dynamics of confined quarks and provides a very general classification of models for soft hadronic interactions. However, before we define and discuss in detail additive versus collective behaviour of quarks of the colliding hadrons we introduce two concepts which we accept as our framework, namely the recombination picture for hadron fragmentation and the notion of repeated collisions of the projectile (or the projectile-like system) in the nucleus.

There are strong indications from hadronic data that quantum numbers of the initial hadrons do not disperse in the bulk of the newly produced particles but are carried by the few fastest collision products. Straight-forward interpretation of this phenomenon in terms of the quark structure of the initial hadrons leads us to the recombination picture in which the quark flavours of the initial hadrons tend to retain a large fraction of the initial hadron momentum and recombine into few particles in the fragmentation region. Several models based on this picture²⁾ have apparently been quite successful phenomenologically, even if they differ in the assumed actual interaction mechanism. It is this mechanism that we would like to see studied experimentally as directly as possible to get deeper insight into the soft quark dynamics. The unique possibility offered in this respect by hadron-nucleus collisions is based on the fact that, according to strong experimental indications, the projectile (or the projectile-like system) traversing the nucleus suffers repeated collisions in the nuclear matter. There are several experimental facts suggesting this behaviour: a) approximate so-called v scaling³⁾ of the A dependence of the average multiplicity; b) attenuation of the forward leading hadronic system⁴⁾; c) dependence of the attenuation effect on whether the secondary has quarks common with the projectile or not as indicated by recent data on π^+ and π^- attenuation in π^-C collisions at 40 GeV/c⁵⁾. We assume also that at high enough energy all fast final hadrons are formed outside the nucleus, i.e., they cannot yet be identified as hadrons in the projectile-like system traversing the nucleus.

We turn now to the main topic of this paper. In additive quark models (AQMs), hadrons are envisaged as compounds of weakly bound constituent (dressed) quarks. Each collision involves (in the first approximation, neglecting multiscatterings à la Glauber) only one constituent quark from each hadron⁶⁾. The others are spectators which recombine with quarks produced in the qq collision into the final hadrons. It is important to stress that in this picture constituent quarks should behave as well-defined entities also in the recombination process. Several versions of the AQM were discussed in the literature, e.g., with or without the leading quark effect in the quark-quark collisions.

By the collective picture we understand one in which hadrons do not have the above two-stage quark structure (bag model, where a bag interacts as a whole, provides a good example of the collective picture of the hadron structure). Consequently each collision involves on equal footing all the initial hadron quark flavours and the same is true for the recombination process. Several particle production models use this picture e.g., the gluon-valence quark model reviewed in Ref. 7) and also many models which do not refer explicitly to the quark structure of hadrons (bremsstrahlung models, eikonal rescattering models etc.).

Our main point is that models of the above two categories lead to different predictions for the quark flavour content of the leading system and, consequently, of the attenuation effect for the different final particles in the fragmentation on nuclei. This difference is essentially independent of any further details of a particular model. However, there is also the question of the over-all strength of attenuation which, evidently, depends on the number of subsequent interactions (SI) of the projectile-like system inside the nucleus. In AQMs, supplemented by the formation length concept, each constituent quark can interact only once⁸⁾. In collective models the number of SI's of the projectile-like system may be unlimited even if one allows for a large formation length of the newly produced hadrons. The most straightforward interpretation of the approximate v scaling implies that the SI cross section is close to the projectile cross section. The problem of constructing the actual collective model of the subsequent collisions is beyond the present considerations^{*)}.

*) If hadrons interact mainly through their glue component then presumably only a fraction of glue is stripped of the hadron in a single (hadron-hadron) collision and the rest recombines with the valence quarks into few fast fragmentation products (as recently suggested in Ref. 9) or, on nuclei, interacts again.

To illustrate the difference between the collective and additive behaviour of quark flavours we present below the predictions of the collective picture based on two different assumptions for the magnitude of the SI cross-section.

To make clear our discussion of the fragmentation on nuclei we first review the use of the recombination picture in hadron-hadron collisions, and at the same time point out the new evidence for this picture coming from the recent data on multipion production¹⁰⁾. The basic picture is that fragmentation yields are determined by the number of quarks with the proper quantum numbers in the leading system. In AQMs for the incident proton we are left after the collision with two spectator quarks (S) : $u_S u_S$ with probability $1/3$, and $u_S d_S$ with probability $2/3$. In the collective picture the leading system is formed by all three quark flavours (uud). In both cases fast mesons are formed via recombination of these quarks with slow (sea) antiquarks. It can be easily shown that in this picture $R_1 = \pi^+/\pi^- = 2$ (R stands for the ratio of multiplicities in the fragmentation region), a prediction already well known. Due to the well known non-universality of the u and d quark distribution functions this prediction should be compared with the total fragmentation multiplicities or near $x \sim 1/3$. The experimental data near $x \sim 1/3$ are compatible with this prediction.

We can easily extend our predictions to the case of fragmentation into multipion systems. We get the ratio $R_2 = \pi^+ \pi^- / \pi^+ \pi^+ = 2$ (outside the ρ -meson band for $\pi^+ \pi^-$ system), and $R_3 = (\pi^+ \pi^-) \pi^+ / (\pi^+ \pi^-) \pi^- = 2$, assuming that the main contributions comes from the events where $\pi^+ \pi^-$ is a resonance. The latter assumption is quite natural in AQMs where there are only two spectator quarks; but also in collective models the probability that all three leading quarks will recombine into mesons is expected to be very small, since in this case the baryon is produced from the sea. Finally, one obtains also $R'_2 = \pi^+ \pi^- / \pi^- \pi^- \gg 1$, since in the $\pi^- \pi^-$ system only one of the mesons can be produced via recombination involving initial hadron quark flavours. All these predictions are in nice agreement with the recent data on the fragmentation into multipion systems¹⁰⁾ (with $x \gtrsim 0.5$). Note that in the multipion systems the x dependent effects in the ratios R_i should be weaker, since some averaging over single quark distributions is involved.

We are now ready to discuss the fragmentation on nuclei. We consider first the AQM framework. Here the first collision of the incident baryon with a nucleus leaves two fast spectators; the second collision leaves only

one spectator, and the third collision leaves no fast spectator quarks at all. Consider now a fast particle system ($x \sim 1$), which can be produced by the recombination of two spectators, i.e., $p \rightarrow p, n, \Lambda, (\pi^+\pi^+), (\pi^+\pi^-)$ outside the p^0 region etc. For the spectra of such systems we have

$$\frac{dN_A(p \rightarrow p, \Lambda, \dots)}{dx} = P_1(A) \frac{dN_1^{(p \rightarrow p, \Lambda)}}{dx} + P_2(A) \frac{dN_2^{(p \rightarrow p, \Lambda)}}{dx} + P_3(A) \frac{dN_3^{(p \rightarrow p, \Lambda, \dots)}}{dx} \quad (1)$$

where $P_i(A)$ is the probability that the projectile has suffered exactly (i) interactions and the $\frac{dN_i}{dx}$ are the distributions after the (i) collisions. Obviously $\frac{dN_1}{dx} = \frac{dN_N}{dx}$ is the distribution in the projectile-nucleon collision, and in AQMs it is due to the recombination of two spectators whereas for $i = 2$ and 3 the distributions are due to the recombination of only one or no spectator, respectively.

For systems which are produced by the recombination of at most one spectator quark e.g., $p \rightarrow \pi^+, \pi^-, (\pi^-\pi^-), p^{0,\pm}$ etc., we get the following predictions :

$$\begin{aligned} \frac{dN_A(p \rightarrow \pi^-, \bar{p}^-, (\pi^-\pi^-) \dots)}{dx} &= (P_1(A) + P_2(A)) \frac{dN_1(p \rightarrow \pi^-, \bar{p}^- \dots)}{dx} \\ &+ P_3(A) \frac{dN_2(p \rightarrow \pi^-, \bar{p}^- \dots)}{dx} \end{aligned} \quad (2)$$

and

$$\begin{aligned} \frac{dN_A(p \rightarrow \pi^+, \bar{p}^+, K_2^+)}{dx} &= (P_1(A) + \frac{2}{3} P_2(A)) \frac{dN_1(p \rightarrow \pi^+, \bar{p}^+ \dots)}{dx} \\ &+ (\frac{1}{3} P_2(A) + P_3(A)) \frac{dN_2(p \rightarrow \pi^+, \bar{p}^+ \dots)}{dx} \end{aligned} \quad (3)$$

Here the dN_1/dx and dN_2/dx are the spectra of mesons containing one or no spectator quarks. Notice that the second collision does not change the spectrum of π^- and also with probability $2/3$ that of π^+ .

A convenient quantity is the relative spectrum $R_A(x) = (dN_A/dx)/(dN_N/dx)$, for which the above arguments lead to the following simple predictions :

$$R_A(x) \Big|_{x \approx 1}^{p, \Lambda, (\pi^+ \pi^+), \dots} = p_1(A) \quad (4)$$

$$R_A(x) \Big|_{x \approx 1}^{\pi^-, p^-, (\pi^- \pi^-), \dots} = p_1(A) + p_2(A) \quad (5)$$

$$R_A(x) \Big|_{x \approx 1}^{\pi^+, p^+, K^+, \dots} = p_1(A) + \frac{2}{3} p_2(A) \quad (6)$$

On the contrary, in the collective picture one expects that the momentum available for the recombination of the initial hadron quark flavours into fast final particles decreases in each collision at approximately equal rate for all three flavours. Therefore, for fragmentation into any system B we obtain

$$\begin{aligned} \frac{dN_A(p \rightarrow B)}{dx} = & p_1(A) \frac{dN_1(p \rightarrow B)}{dx} + p_2(A) \frac{dN_2(p \rightarrow B)}{dx} + \\ & + p_3(A) \frac{dN_3(p \rightarrow B)}{dx} + \dots \end{aligned} \quad (7)$$

where the dN_i/dx denotes again the spectrum after (i) collisions and

$$R_A(x) \Big|_{x \approx 1}^{p \rightarrow B} = p_1(A) \quad (8)$$

Comparison of (4)-(6) with (8) shows that experimental study of the quantum number dependent effects will allow to distinguish between the two pictures considered.

To provide quantitative illustration to our discussion we have calculated numerically the x dependence of $R_A(x)$ in both approaches. In the collective picture the spectra dN_i/dx after the successive collisions have been calculated using the convolution transformation :

$$\frac{dN_{i+1}}{dx} = \int \frac{dx_L}{x} \frac{dN_L^i(x_L)}{dx_L} \cdot \frac{dN_1(x/x_L)}{d(x/x_L)} \quad (9)$$

where the dN_1/dx is the spectrum of the particle of interest in the projectile-nucleon collision, and dN_L^i/dx_L is the spectrum of the projectile-like system after the i -th collision. This latter spectrum is also given by Eq. (9) with the dN_1/dx replaced by dN_L^1/dx_L , the leading particle spectrum in hN collisions which, according to experimental data, is, to a good approximation, x independent. In our AQM we use an analogous convolution transformation to connect the spectra which differ by the number of the spectator quarks involved in recombination [see Ref. 11) for more detail]. This is an approximate but quite natural procedure for the AQM with the leading quark effect. This version seems to us more realistic than versions with inelasticity $\simeq 1$ in the qq collisions. In the latter version part of the initial hadron quantum numbers disperses in the newly produced particles in the central region. For instance, let us consider charge retention in channels with zero initial charge, like π^-p or $\bar{p}p$. The quantity $D = 1 - \int_0^{Y_{\max}} \left(\frac{dN^-}{dy} - \frac{dN^+}{dy} \right) dy$ provides a direct measure of the projectile charge which has dispersed in the production process. For the π^-p collision the AQM without the leading quark effect gives $D = 5/12$. The experimental value for D_{π^-p} is decreasing with energy and at $p_{\text{LAB}} = 360 \text{ GeV/c}$ it is already well below that prediction¹²⁾. The version with the leading quark effect gives $D = 0$ asymptotically as indeed is suggested by the trend of the present data.

For the SI probabilities in the collective picture we consider two versions: one with the SI cross section σ_{in} equal to $\sigma_{\text{in}}^{\text{pp}}$, as has been suggested by Busza et al.³⁾ on the basis of the v scaling (CM1), and another (CM2) with gradually decreasing cross sections which we choose to be the same as in the AQM ($\sigma_1 = \sigma_{\text{in}}^{\text{pp}}$, $\sigma_2 = 2/3\sigma_1$, $\sigma_3 = \sigma_1/3$, $\sigma_i \geq 4 = 0$). A convenient parametrization for the nuclear spectra is $R_A(x) = A^{\alpha(x)}$. In the Figure we present the x dependence of the $\alpha(x)$ calculated as explained above. Also shown are the recent data on the $p \rightarrow \Lambda$ fragmentation on nuclei⁴⁾. We observe that these data agree well with the CM2 and AQM predictions. The CM1 gives somewhat too strong an attenuation, so that the data give some evidence for the decrease of the SI cross sections of the projectile-like system in the nucleus. Secondly, the collective

and additive pictures can be easily discriminated experimentally. In collective models, $\alpha_{p \rightarrow \Lambda, p} \approx \alpha_{p \rightarrow \pi}$ whereas the difference between $\alpha_{p \rightarrow \pi}$ and $\alpha_{p \rightarrow \Lambda, p}$, predicted by the AQM, is large enough to be detected with the available experimental accuracies, as shown by the data on the $\alpha_{p \rightarrow \Lambda}(x)$. We note also that according to AQMs the $\alpha_{\pi^+\pi^-}(x)$ should be different in and outside the ρ region : $\alpha_{p \rightarrow \rho} \approx \alpha_{p \rightarrow \pi}$, $\alpha_{p \rightarrow 2\pi} \approx \alpha_{p \rightarrow \Lambda}$ so that the ratio $\rho/(2\pi)_{\text{non-res}}$, as well as $\pi^-\pi^-/\pi^+\pi^-$ ratio, should increase with the atomic number of the nucleus. In collective models, the relative ratios at $x \approx 1$ of particles from projectile fragmentation should be target-independent. A precise data on $p \rightarrow \pi, K$ fragmentation on nuclei at high energies are needed for the crucial test of the two pictures discussed.

The data by Allaby et al.¹³⁾ on $P_{\text{lab}} = 19.2 \text{ GeV/c}$ pA interactions are not decisive since at this energy the formation lengths are comparable to, and even smaller than, the dimensions of nuclei. This leads to an additional absorption of fast particles which is not present in our considerations. Our discussion is relevant if at high enough energies there is no attenuation of fast secondaries which have no common constituent quarks with the projectile.

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FIGURE CAPTION

Plotted are the exponents α for the fragmentation spectra in proton-nucleus interactions, predicted by the additive quark model (AQM) and by the two variants of the collective model (CM1 and CM2). Also shown are the data of Heller et al. ⁴⁾ for the fragmentation $p \rightarrow \Lambda$ at 300 GeV/c.