Multiple-Quark Stripping in Proton-Nucleus Collisions at 100 GeV

K. Werner, J. Hüfner, M. Kutschera,[a] and O. Nachtmann
Institut für Theoretische Physik der Universität, Heidelberg, Federal Republic of Germany, and Max-Planck-Institut für Kernphysik, Heidelberg, Federal Republic of Germany
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The momentum distributions are calculated for the pions and protons which are produced in a proton-nucleus collision. We assume that in each nucleon-nucleon interaction a quark or a quark-antiquark pair is removed from the projectile. The final hadron distribution can then be expressed in terms of quark distribution functions and fragmentation functions which are both taken from lepton-nucleon collisions.

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What happens to a 100-GeV proton traversing a nucleus? Depending on the impact parameter it collides with one or several nucleons along its trajectory. In the first inelastic collision it is excited, but as a result of time dilation it does not reach an asymptotic state before interacting with the next nucleon. It is only far outside the target nucleus that the excited projectile or what has remained of it fragments into a number of hadrons which are then observed. What is the nature of the excited projectile which cannot be observed directly but only via its fragmentation products? And how does its state change with increasing number ν of projectile-nucleon collisions? In order to answer these questions we analyze the pion and proton momentum distributions obtained by Barton *et al.*,[1] for proton-nucleus (pA) collisions at incident momentum $p_0 = 100$ GeV/c and for several target nuclei ranging from hydrogen to lead.

Unfortunately, nuclear collisions are always an incoherent superposition of events with different numbers ν which is due to the spherical shape of a nucleus. The cross section for an inclusive reaction $p+A \to h+X$ in which the momentum $\mathbf{p}=(p_\parallel, \mathbf{p}_\perp)$ and the energy E of a hadron h are measured can be decomposed into a series

$$E\frac{d^3\sigma^{pA\to hX}}{dp^3}(x,\mathbf{p}_\perp)=\sum_{\nu\geq 1}\sigma_\nu^{pA} f_\nu^{p\to h}(x,\mathbf{p}_\perp), \qquad (1)$$

where $x=p_\parallel/p_0$. The cross sections σ_ν^{pA} for a pA collision in which the projectile collides with exactly ν target nucleons are calculated according to Glauber and Matthiae[2]:

$$\sigma_\nu^{pA}=\int d^2b\frac{T^\nu(b)}{\nu}e^{-T(b)},$$

$$T(b)=\sigma_{\text{in}}^{pN}\int dz\,\rho_A(\mathbf{b},z), \qquad (2)$$

where σ_{in}^{pN} is the inelastic proton-nucleon cross section and $\rho_A(\mathbf{r})$ the matter density of the target nucleus. The functions $f_\nu^{p\to h}(x,\mathbf{p}_\perp)$ contain the important information. They describe the momentum distribution of the hadron h which is formed in the fragmentation of the projectile after ν collisions. We have developed a method to obtain the functions $f_\nu(x,\mathbf{p}_\perp)$ from the experimental pA cross sections essentially by inversion of Eq. (1).[3] Figure 1 shows the functions $f_\nu^{p\to\pi^+}(x,\mathbf{p}_\perp)$ obtained in this way from the data of Barton *et al.* Two remarkable properties can be read from this figure:

(i) The functions $f_1^{p\to\pi^+}$ and $f_2^{p\to\pi^+}$ differ from each other in an unexpected way. For large pion momenta, i.e., $x\to 1$, the distribution f_1 goes to zero

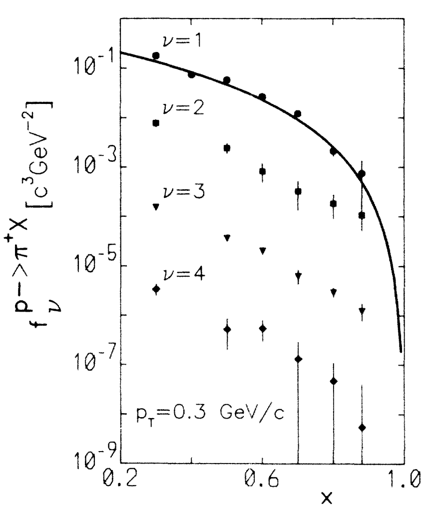

FIG. 1. The momentum distributions $f_\nu^{p\to\pi^+}(x,\mathbf{p}_\perp)$ of positive pions which arise in the fragmentation after the proton has collided with ν target nucleons. The "experimental" points are obtained by analysis of the experiment by Barton *et al.* (Ref. 1) for $p+A\to\pi^+ + X$ according to the method of Ref. 3. The functions f_ν for different ν have been multiplied by a factor $30^{-(\nu-1)}$ in order to separate them. The solid line is (up to a factor 1.3) the function $D^{ud\to\pi^+}$ for the fragmentation of a ud diquark into a π^+. Note the change in shape between $\nu=1$ and $\nu=2$.

more rapidly than f_2. This means that the pions arising from the fragmentation of a proton which has collided twice are on the average more energetic than in the case $\nu=1$. This contradicts the naive expectation that multiple scattering means increased energy loss and nothing else. We interpret this observation as implying that the *nature* of the excited projectile changes at least between $\nu=1$ and $\nu=2$. No similarly dramatic effects are visible when we compare $\nu=2$ and $\nu\geqslant 3$. To our knowledge this is the first time that qualitative new effects are seen in multiple scattering.

(ii) We have compared the distribution function $f_1^{p\to\pi^+}(x,\mathbf{p}_\perp)$ in Fig. 1 to the fragmentation function $D^{ud\to\pi^+}(x,\mathbf{p}_\perp)$ describing the hadronization of a *ud* diquark as measured in lepton-nucleon scattering.[4] By fitting the overall normalization we find

$$x^{-1}f_1^{p\to\pi^+}(x,\mathbf{p}_\perp)\approx 1.3D^{ud\to\pi^+}(x,\mathbf{p}_\perp) \tag{3}$$

over the entire experimental range $0.3\leqslant x\leqslant 0.88$. This agreement in shape can hardly be an accident! We interpret the observation as implying that the observed pion in pN collisions arises from the fragmentation of a diquark which carries nearly all the momentum of the projectile proton (cf., however, the interpretation by Desai and Sukhatme[5]). However, as we shall see, this is not the complete description of the projectile remnant even after one collision.

What is then the nature of the projectile remnant after ν collisions? We shall use empirical fragmentation functions for the hadronization of quarks and diquarks in order to identify the "fingerprints" of the projectile remnant. In this way we propose the following picture—a modification of the model by Capella and Tran Thanh Van[6]—for the interaction of a proton with ν nucleons: In each interaction either a quark (q) or a quark-antiquark $(q\bar{q})$ pair is stripped off the projectile. The projectile loses the momentum Δx and the baryon number ΔB which are carried away by the q or $q\bar{q}$, respectively, in each collision. After ν collisions the projectile remnant has then the baryon number $B=n/3$ with a probability $A_\nu^{(n)}$. We allow only quark, diquark, and triquark components, i.e., $n=1,2,3$. The longitudinal momentum distribution of this $B=n/3$ object is described by a function $\rho_\nu^{(n)}(x)$. It fragments into the observed hadrons according to

$$f_\nu^{p\to h}(x,\mathbf{p}_\perp)=\sum_{n=1}^{3}A_\nu^{(n)}\int_0^1 dx'\,\rho_\nu^{(n)}(x')\frac{x}{x'}D^{nq\to h}\left(\frac{x}{x'},\mathbf{p}_\perp\right), \tag{4}$$

where $D^{nq\to h}(z,\mathbf{p}_\perp)$ is the fragmentation of a system with baryon number $n/3$ into a hadron h. This function is independent of ν and is taken, where available, from experiment. For simplicity we have suppressed all flavor indices, though they have been taken into account in the computation.

The momentum distributions $\rho_\nu^{(n)}(x)$ of the projectile remnant are calculated from the empirical[7] distribution functions $q(x)$ and $\bar{q}(x)$ of quarks and antiquarks in a proton. We use the prescription

$$\rho_\nu^{(n)}(1-x)=c\int\delta\left(x-\sum_{i=1}^{k}z_i-\sum_{j=1}^{m}(x_j+x_j')\right)\prod_{i=1}^{k}dz_i\,q(z_i)\prod_{j=1}^{m}dx_j\,dx_j'\,q(x_j)\bar{q}(x_j') \tag{5}$$

for a situation where $k=3-n$ quarks and m $q\bar{q}$ pairs are removed from the projectile $(\nu=k+m)$. As in the model of Ref. 6 a cutoff parameter has to be introduced in $\bar{q}(x)$ for small x. We fix it so that the empirical energy loss in pA collisions[8] is reproduced. The constant c in Eq. (5) is determined by the normalization requirement $\int dx\,\rho=1$.

Assuming in each collision either a q or a $q\bar{q}$ to be removed with probabilities $1-w$ and w, respectively, we can calculate the coefficients $A_\nu^{(n)}$ in Eq. (4) to be

$$A_\nu^{(n)}=c_\nu(c_{3-n}^{\nu})(1-w)^{3-n}w^{\nu-(3-n)} \tag{6}$$

for $n=1,2,3$ and 0 otherwise. The constant c_ν is fixed by the normalization $\sum_n A_\nu^{(n)}=1$. The probability w is essentially a free parameter. We use it to obtain an overall good agreement with experiment. Values of w between 0.2 and 0.4 give acceptable descriptions of the data; in this paper we present results for $w=0.3$. We can get a rough estimate of the magnitude of w by identifying single diffractive excitation in pp collisions with the removal of a $q\bar{q}$ pair in our picture. In this case $w\approx w'=\sigma_{\rm SD}^{pN}/\sigma_{\rm in}^{pN}$ where $\sigma_{\rm SD}^{pN}$ is the cross section for single diffractive excitation. Values for w' vary between 0.1 and 0.2[9] and are not too far from the value $w=0.3$ used here.

The functions $D^{nq\to h}(x,\mathbf{p}_\perp)$ in Eq. (4) describe the fragmentation of a remnant with $B=n/3$ into hadrons h. For $n=1$ we use the empirical quark fragmentation functions.[4] The measured fragmentation function for "nucleon minus quark," i.e., on the target side of deep inelastic lepton-nucleon scattering, is used as the "diquark" fragmentation function $(n=2)$. Finally, for $n=3$, "triquark," we have no data and therefore assume

$$D^{3q\to h}(x)=\begin{cases}\delta(1-x) & \text{for } h=\text{proton},\\ 0 & \text{for all other hadrons}\end{cases} \tag{7}$$

for the experimental range $x>0.3$ of observed momenta. Equation (7) is admittedly oversimplified but it at least satisfies the sum rule for the mean momentum. Furthermore, it reflects the asymmetry that the

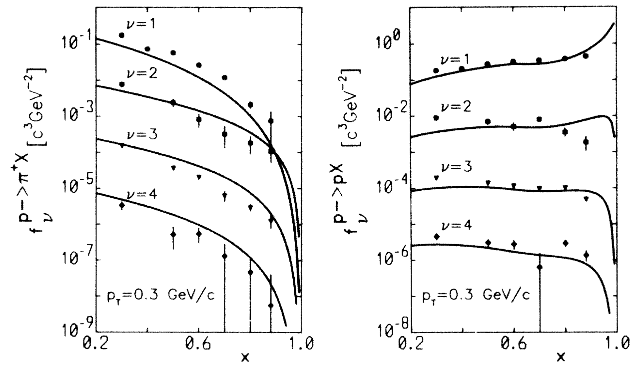

FIG. 2. The "experimental" momentum distributions $f_\nu^{p\to h}(x,\mathbf{p}_\perp)$ compared with our calculation (solid line). Positive pions on the left, protons on the right-hand side. Again the distributions are multiplied by $30^{1-\nu}$ for better display.

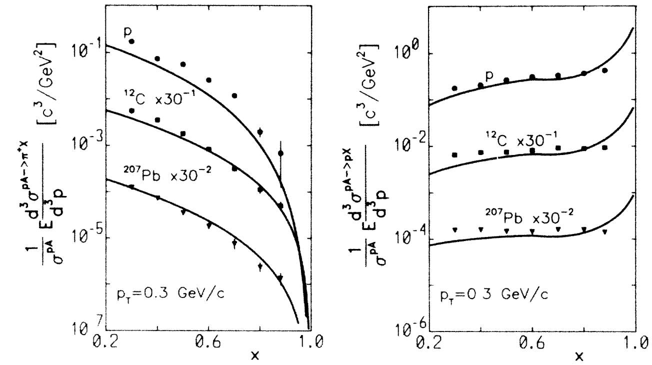

FIG. 3. The inclusive cross sections $(\sigma_R^p A)^{-1} \times E d^3\sigma^{pA\to hX}/dp^3$ for outgoing hadrons $h=\pi^+$ (left-hand side) and $h=p$ (right-hand side). The experimental points by Barton *et al.* (Ref. 1) are compared to our calculation (solid line). The values for ^{12}C are multiplied by $\frac{1}{30}$ and those for Pb by $\frac{1}{900}$.

projectile is a proton (we do not allow the fragmentation into fast neutrons). Since triquark fragmentation is most important in the proton spectra for $x > 0.7$, we expect any associated mesons only at $x < 0.3$ and hence outside the range of the experiment by Barton *et al.*,[1]

Figures 2 and 3 show the results of our calculation in comparison with the data. We display the functions $f_\nu^{p\to h}(x,\mathbf{p}_\perp)$ as well as the nuclear cross sections $E\, d^3\sigma^{pA\to hX}/d^3p(x,\mathbf{p}_\perp)$ as a function of the longitudinal momentum x for protons as well as π^+ for the outgoing hadron h. Calculated and empirical curves agree well in shape and in magnitude mostly better than a factor 2. Note that nearly all the input information, distribution and fragmentation functions, is taken from lepton-nucleon experiments.

Of course, our calculation is not the first one to investigate projectile fragmentation in pA collisions. Our model of the reaction mechanism is closest to the multichain model by Capella and Tran Thanh Van,[6] but we go beyond by also allowing for the stripping of *two* quarks similar to Anisovich, Shabelsky, and Shekhter[10] and by also taking into account that a $q\bar{q}$ pair can be removed in the first collision. In the realization of our model we use information from lepton-nucleon scattering wherever available, while in Ref. 6 effective functions are chosen to reproduce the results from $pp\to hX$ reactions. Daté, Gyulassy, and Sumiyoshi[11] start from an equation similar to our Eq. (4) without the sum over n and also introduce effective fragmentation functions fitted to pp collisions. These authors do not specify the nature of the projectile remnant. In a microscopic approach, Hwa[12] assumes that the projectile proton decays into three quarks which propagate independently through the nucleus before they hadronize.

What is then the nature of the fastest remnant of a 100-GeV/c proton which has traversed a nucleus and has collided ν times along its way? According to our picture the remnant is an incoherent superposition of a triquark and a diquark for $\nu=1$. In the next collision, another quark or a qq pair can be stripped off so that the remnant can also be found in a one-quark state. The appearance of the one-quark component for $\nu=2$ explains the unexpected phenomenon discussed in connection with Fig. 1: A quark easily fragments into a fast pion while baryons from the fragmentation of a diquark tend to be fast and pions slow. The hadrons in the experimental momentum range $x \geqslant 0.3$ essentially arise only from the fragmentation of the fastest part of the projectile remnant; the fragmentation product of the target nucleons and the stripped-off q and $q\bar{q}$ appear in the range $x \leqslant 0.3$.

We think we have been able to identify positively the fingerprints of the fastest projectile remnant in terms of a mixture of quark, diquark, and triquark contributions. We also have been able to show that qualitative new phenomena appear in multiple scattering. A detailed account of this work is in preparation.[13]

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[a]On leave of absence from the Institute of Nuclear Physics, 31342 Kraków, Poland.

[1]D. S. Barton *et al.*, Phys. Rev. D **27**, 2580 (1983).

[2]R. J. Glauber and G. Matthiae, Nucl. Phys. **B21**, 135 (1970).

[3]J. Hüfner, M. Kutschera, B. Liu, and K. Werner, Phys. Lett. **166B**, 31 (1986).

[4]P. Allen *et al.*, Nucl. Phys. **B214**, 369 (1983); M. Arneodo *et al.*, CERN Report No. CERN-EP/84-148 (to be published).

[5]B. R. Desai and U. P. Sukhatme, Z. Phys. C **24**, 277 (1984).

[6]A. Capella and J. Tran Thanh Van, Z. Phys. C **10**, 249 (1981).

[7]M. Glück, E. Hoffman, and E. Reya, Z. Phys. C **13**, 119 (1982).

[8]A. Klar and J. Hüfner, Phys. Rev. D **31**, 491 (1985).

[9]A. Wroblewski, in *Proceedings of the Fourteenth International Symposium on Multiparticle Dynamics, Granlibakken 1983,* edited by P. Yager and J. F. Gunion (World Scientific, Singapore, 1984).

[10]V. V. Anisovich, Yu. M. Shabelsky, and V. M. Shekhter, Nucl. Phys. **B133**, 477 (1978).

[11]S. Daté, M. Gyulassy, and H. Sumiyoshi, Phys. Rev. D **32**, 619 (1985).

[12]R. C. Hwa and M. S. Zahir, Phys. Rev. D **31**, 499 (1985).

[13]K. Werner *et al.*, to be published.