Simple Space-Time Description of High-Energy Hadron-Nucleus Collisions

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A simple space-time description of high-energy hadron-nucleus collisions is presented. The model is based on the two-sheet description of soft multiparticle production in hadron-hadron collisions, and can be formulated in a parton framework. This zero-parameter model agrees well with the general features of hadron-nucleus data.

Two general features have emerged from high-energy hadron-nucleus (hA) experiments during the last few years.[1] One defines $R_A \equiv \langle N_{ch}\rangle/\langle N_{ch}\rangle_{hp}$ and $\bar{\nu} \equiv A\sigma_{in}^{hp}/\sigma_{in}^{hA}$. The variable $\bar{\nu}$ can be interpreted to be the averaged number of inelastic collisions experienced by h as it traverses through a nucleus with A nucleons.

One feature of the data is that R_A is small and may be approximately parametrized as $R_A \simeq a + b\bar{\nu}$, with $a \simeq \frac{1}{2} \simeq b$,[2] and a, b, and $\bar{\nu}$ are roughly energy independent in the Fermilab energy range $\simeq$50–300 GeV.[2] The second feature is that the rapidity (or pseudorapidity) distribution dN/dy ($dN/d\eta$) is approximately target independent in the projectile-fragmentation region and increases roughly as $\bar{\nu}$ in the target-fragmentation region.

Because of the exciting possibility of extracting the space-time development of hadron-hadron (hh) collisions, hA collisions have generated tremendous interest during the last few years, both experimentally and theoretically.[3] In this paper we present a simple space-time description of hA collisions. Our model is motivated by the two-sheet description in dual topological unitarization (DTU),[4] but it can also be phrased in the parton language.[5-7]

In DTU, soft multiparticle production for high-energy hh (to be specific, say pp) collisions is described by the two-sheet structure shown in Fig. 1. Each sheet corresponds to a multiperipheral chain generated by a quark and a diquark and the two chains overlap in rapidity. The pomeron is generated through the unitarity sum of the square of the multiparticle production amplitude. Squaring and sewing the amplitude depicted in Fig. 1 results in the cylinder topological pomeron.

In terms of the colored quark-parton language, one can reinterpret the DTU pomeron; as the result of the interaction between the projectile and the target, a negative small-Feynman-x quark of the target is associated with the positive large-x diquark of the projectile, and a positive small-x quark of the projectile is associated with the negative large-x diquark of the target. This results in two hadronic systems; each hadronic system is made up of a color-$\underline{3}$ quark and a color-$\underline{3}^*$ diquark. We call these two hadronic systems the excited projectile system (EPS) and excited target system (ETS), respectively.[8] Because of the large difference in momentum between the quark

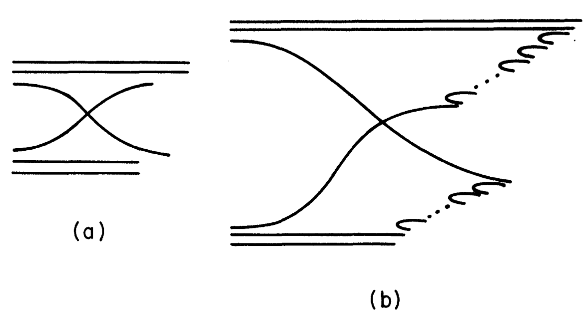

FIG. 1. The two-sheet model for multiparticle production: (a) at short times, (b) at long times.

and the diquark in each hadronic system, the spatial separation between them increases with time, and the color-confining mechanism then presumably comes into play and causes each hadronic system to evolve into a jet of hadrons after a characteristic time τ_0 (in its own rest frame) has elapsed.

It is reasonable to take τ_0 to be the typical lifetime of a heavy nucleon resonance,[9] i.e., $\tau_0 \simeq m_\pi^{-1}$ or $(2m_\pi)^{-1}$. Then at high energy, the lifetime of the EPS in the laboratory will be greatly Lorentz dilated. Therefore, the first EPS does not have time to evolve into its final multihadron state before it reaches the next nucleon in A, whereas the ETS will have a large probability of evolving into its final multihadron state. The above process repeats itself until the EPS leaves A after $\bar{\nu}$ inelastic collisions. This results in one EPS and $\bar{\nu}$ ETS, and therefore R_A in this approximation should be given by[10]

$$R_A \simeq \tfrac{1}{2} + \tfrac{1}{2}\bar{\nu}, \tag{1}$$

in agreement with the data.

Because of a small probability that the ETS's also do not evolve into their final states before reaching the succeeding nucleons and thereby undergo further low-energy interactions, we expect a small additional multiplicity in the small-y region. We neglect the further cascades of the final hadrons from the evolution of the ETS's, because the energies involved are even smaller. Therefore, our model predicts that R_A should be slightly larger than that given by (1), and the excess multiplicity should be in the small-y region. Since as the result of the collision of h with A, there is one EPS and $\bar{\nu}$ ETS, $(dN/dy)_{hA}$ should be approximately the same as $(dN/dy)_{hp}$ in the large-y region,[11] and $(dN/dy)_{hA} \simeq \bar{\nu}(dN/dy)_{hp}$ in the small-y region, in agreement with the data.

We now make quantitative the qualitative discussion given above by choosing a specific formulation of the two-sheet model. The model we choose is that of Capella *et al.*[5] We emphasize that our results are fairly insensitive to the specific hh model (as long as it agrees with the hh data) used as input.[12] We choose the above model because it is simple, well defined, and above all, separates the contribution of the ETS from that of the EPS.

Denote the laboratory rapidity by y; then the model of Ref. 5 gives

$$(dN/dy)_{pp} = f\big(y - (y_{\text{c.m.}} + \Delta)\big) + f\big((y_{\text{c.m.}} - \Delta) - y\big), \tag{2a}$$

where

$$f(\tilde{y}) = \begin{cases} 1.20(1-\xi)^3, & \tilde{y} \geq 0 \\ \dfrac{0.05 + 1.15(1-\xi)^2}{1 - 0.5\xi}, & \tilde{y} < 0, \end{cases} \tag{2b}$$

$$\Delta = \tfrac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right), \quad \xi = \left|\frac{\mu_T}{\bar{P}}\sinh\tilde{y}\right|, \tag{2c}$$

$$\beta = \frac{(2x_0 - 1)P}{(x_0^2P^2 + 4m_Q^2)^{1/2} + [(1-x_0)^2P^2 + m_Q^2]^{1/2}}, \tag{2d}$$

$$\bar{P} = \frac{x_0P - \beta(x_0^2P^2 + 4m_Q^2)^{1/2}}{(1-\beta^2)^{1/2}}. \tag{2e}$$

and where they used $m_Q = 0.33$ GeV for the quark mass and $\mu_T = 0.33$ GeV for the transverse pion mass. In Eq. (2), P is the incident momentum in the c.m. system and $y_{\text{c.m.}}$ is the c.m. rapidity in the laboratory, β (Δ) is the velocity (rapidity) of the EPS's c.m. relative to the overall c.m. and $\bar{P}$ is the momentum of the projectile diquark in the EPS's c.m. The expression f is related to the quark and diquark fragmentation functions and is determined from e^+e^- data and dimensional counting rules.[13] The first and second term in (2a) correspond, respectively, to the EPS and ETS contributions. Equation (2) does not include the forward proton.

It is then straightforward to work out the kinematics of the $(\bar{\nu} - 1)$ succeeding inelastic interactions in hA collisions and conclude that the kinematics for the second collision is approximately just that of the first collision except for the substitution $P \to P[x_0(2-x_0)]^{1/2}$. Similar remarks apply for subsequent collisions.

In Fig. 2 we show the results of these zero-parameter calculations for $dN/d\eta$ for 200-GeV p-initiated reactions for $\bar{\nu} = 2, 3, 4$, as well as the $\bar{\nu} = 1$ input. The model calculations are in good agreement with the data,[14] except in the small-η bins where, as discussed before, we expect the model calculations to underestimate the multiplicity. The results for R_A are shown in Fig. 3. Again, the model calculations are approximately equal to (but, as expected, slightly less than) the data. Our model predictions for $dN/d\eta$ also agree well with the data of Busza *et al.*[1] at 50 and 100 GeV. These comparisons and higher-energy predictions will be presented elsewhere. Inasmuch as $\langle N_{ch}\rangle$ and dN/dy for pp and πp are nearly the same, our model predicts that these quantities for pA and πA should be approximately the same for the same $\bar{\nu}$, again in agreement with data.[1] In our model the elasticity for pA is only slightly smaller than for pp, also in agreement with the

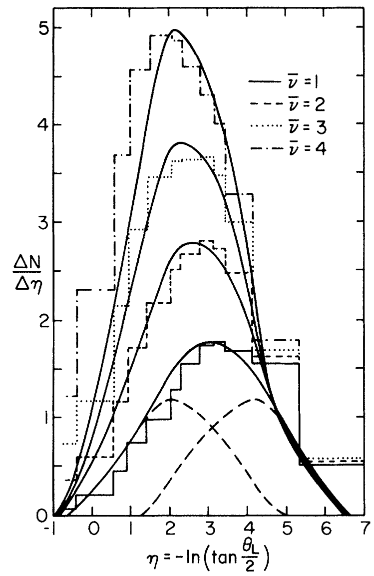

FIG. 2. Laboratory pseudorapidity distributions for *pA* collisions at 200 GeV. Solid lines are our curves; the $\bar{\nu}=1$ curve is the input. Also shown are the individual contributions (dashed curves) of the EPS and ETS as given by Eq. (2). The histograms are the data of Ref. 1a.

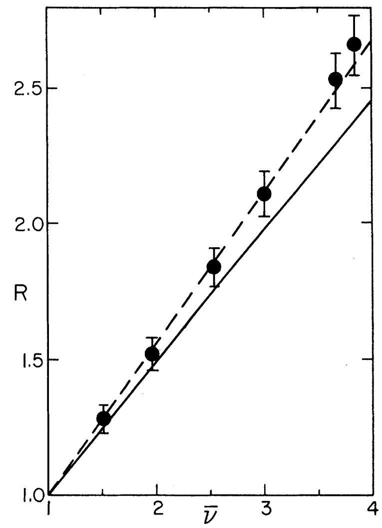

FIG. 3. Integrated multiplicity ratio R_A vs $\bar{\nu}$ for *pA* collisions at 200 GeV. Data points with typical errors of ± 4% are from Ref. 1a. The dashed line and solid line are our results with and without including further interactions of the ETS as mentioned in the text.

trend of the data.[15]

As mentioned earlier, we expect an additional multiplicity for small η. Taking $\tau_0 \simeq (2m_\pi)^{-1}$, one obtains the mean probability of an ETS reaching the next nucleon in A before evolving into its final state; then within the same two-sheet model, it is straightforward combinatorics to trace its subsequent interactions with the succeeding nucleons. The result[16] for R_A after adding this additional contribution is shown as the dashed curve in Fig. 3.

We end with a few remarks. As already discussed in Footnote 8, our model is consistent with short-range dominance and is different from the old two-fireball model.[17] In the two-phase model,[18] the first collision gives rise to an excited hadronic phase which has a flat distribution over the entire rapidity range, and this entire excited tube undergoes further interactions, whereas in our model, the EPS while traversing A does not have much hadronic matter within the rapidity interval defined by its diquark and quark. Because of the above difference, the predicted dN/dy is different even for the same *hh* input. In the modified cascade model,[19] multi-bare-hadrons are immediately produced but it takes time to dress up these bare particles; consequently, the subsequent inelastic interactions of fast secondaries are suppressed. In the present model, the intermediate state is just one EPS and one or more ETS, and cascading (except for very small y) just does not exist. It is an open question whether these two methods of freezing the degrees of freedom are really equivalent or different descriptions.

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[1a]W. Busza *et al.*, in *Proceedings of the Eighteenth International Conference on High Energy Physics, Tbilisi, U. S. S. R., 1976*, edited by N. N. Bogolinkov *et al.* (The Joint Institute for Nuclear Research, Moscow, U. S. S. R., 1977).

[1b]W. Busza *et al.*, Phys. Rev. Lett. 34, 836 (1975), and 39, 1499 (1977), and 41, 285 (1978), and Fermilab Report No. FERMILAB-PUB-79/47-EXP 7185.178 (unpublished); J. R. Florian *et al.*, Phys. Rev. D 13, 558 (1976).

[2]The constant *b* (*a*) is slightly larger (smaller) than 1/2.

[3]See, e.g., A. Bialas, in Proceedings of the First Workshop on Ultra-Relativistic Nuclear Collisions, Berkeley, 1979 (unpublished), and Fermilab Report No.

FERMILAB-Conf-79/35-THY (to be published).

[4a]See, e.g., G. F. Chew and C. Rosenzweig, Phys. Rep. 41C, 263 (1978).

[4b]For the similarity between the DTU and the dual-resonance-model pomerons, see C. B. Chiu and S. Matsuda, Nucl. Phys. B134, 463 (1978); P. Aurenche and L. Gonzalez-Mestres, Phys. Rev. D 18, 2995 (1978).

[5]A. Capella, U. Sukhatme, C.-I Tan, and J. Tran Thanh Van, Phys. Lett. 81B, 68 (1979).

[6]A. Capella *et al.*, Institut de Physique Nucléaire d'Orsay Report No. LPTPE 79/23 (to be published).

[7]G. Cohen-Tannoudji *et al.*, Centre d'Etudes Nucléaires de Saclay Report No. DPh-T/79-97 (to be published), and references therein.

[8]Unlike the old fragmentation model [C. Quigg, J.-M. Wang, and C. N. Yang, Phys. Rev. Lett. 28, 1290 (1972); R. Hwa, Phys. Rev. Lett. 26, 1143 (1971); M. Jacob and R. Slansky, Phys. Rev. D 5, 1847 (1972)], this DTU two-chain model is consistent with short-range dominance. Furthermore, at asymptotic energies, our two chains overlap completely in rapidity except for two finite regions at the two ends. Even though we use the words projectile and target to describe the outgoing systems, the quark partons from which they are formed are not the same as those of the initial projectile and target.

[9]For example, for the specific model considered later, the mass of each hadronic system is ~5 GeV.

[10]Because of the peaking of the diquark x near 1 (Refs. 6 and 7) energy-momentum conservation correction to this result is small.

[11]Since the EPS has a slightly smaller energy than its parent, $(dN/dy)_{hA}$ is slightly smaller than $(dN/dy)_{hp}$ for $y \sim y_{max}$, in agreement with data. D. Chaney *et al.*, Phys. Rev. Lett. 40, 71 (1978).

[12]For example, the more refined version of Ref. 6 gives essentially the same conclusions.

[13]In Eq. (2) we use 0.92 for x_0 and 1.20 for the normalization of f at $\xi=0$, instead of the respective numbers 0.95 and 1.35 of Ref. 5. There are two reasons for this small change. Ours gives better agreement with the pp data of Busza *et al.*, which is the input for our model's pA calculations. Secondly, a smaller x_0 gives a smaller rise over the energy range $\sqrt{s} \approx 20$-60 GeV for the central height of pp collisions, consistent with our belief that at least part of this rise is due to the threshold production of $N\bar{N}$ clusters [C.-I Tan and D. M. Tow, Phys. Rev. D 9, 2176 (1974); C. B. Chiu and D. M. Tow, Phys. Rev. D 15, 3313 (1977)]. We have checked that our parametrization is equally consistent with the e^+e^- data from which it was determined (Ref. 5). The peaking of the diquark x at $x_0 \simeq 1$ is due to the peaking of the valence quark structure function near $(1-x) \simeq 0$. In DTU language, $x \simeq 1$ (or 0) corresponds to ordinary Reggeon (or exotic meson) exchange (Refs. 4b, 6, and 7).

[14]Recall that we are considering only inelastic events and that the forward proton contribution has not been included in our $\bar{\nu}=1$ input. This is the reason for the excess near $\eta \sim 5$.

[15]D. Chaney *et al.*, Phys. Rev. D 19, 3210 (1979).

[16]Details will be presented elsewhere.

[17]A. Dar and J. Vary, Phys. Rev. D 6, 2412 (1972); P. M. Fishbane and J. S. Trefil, Phys. Rev. D 9, 168 (1974).

[18]P. M. Fishbane and J. S. Trefil, Phys. Lett. 51B, 139 (1974).

[19]G. Bialkowski, C. B. Chiu, and D. M. Tow, Phys. Lett. 68B, 451 (1977), and Phys. Rev. D 17, 862 (1978); M. Hossain and D. M. Tow, to be published; P. Valanju, E. C. G. Sudarshan, and C. B. Chiu, to be published.