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Scaling Phenomenon in Relativistic Nucleus-Nucleus Collisions*

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Cheuk-Yin Wong
Oak Ridge National Laboratory
Oak Ridge, TN 37830

and

R. Blankenbecler
Stanford Linear Accelerator Center
Stanford, CA 94305

Abstract

We introduce new scaling variables for proton and pion production in relativistic nucleus-nucleus collisions which are the generalizations of the Feynmann scaling variable. They allow a simple description of the cross sections at the forward and backward angles.

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Recent experimental and theoretical studies[1-6] of nucleus-nucleus collisions in the energy range of a few GeV per nucleon indicates that the use of the Feynmann variable x_F should lead to scaling in the case of forward pion production.[1,2] However, x_F scaling was not observed in proton production[3,4] or in backward pion production.[5] It is desirable to look for new scaling variables so that the experimental data can be better represented and the underlying physics of the scaling phenomenon understood.

The proper scaling variable depends on the reaction mechanism. In the reaction $A+B \to C+X$, the two dominant processes[7] of interest are the direct fragmentation and the hard-scattering process. In the direct projectile fragmentation process the subsystem C is emitted directly from the beam particle B without scattering, while the complementary partner interacts with the target nucleus A. The cross section is proportional to the probability $G_{C/B}(x_D,\vec{C}_T)$ of finding a subsystem C in the projectile B with transverse momentum $\vec{C}_T$ and fractional momentum x_D defined by

$$x_D = \frac{C_o + C_Z}{B_o + B_Z} = x_F \, x_{max} \quad (1)$$

where we have used A, B, and C to denote also the four-vectors of A, B, and C, respectively. In terms of the relativistic invariant $s = (A+B)^2$ and the usual λ-function,[2] we have

$$x_{max} = \frac{s-D^2 + C^2 + \lambda(s,D^2,C^2)}{s-A^2 + B^2 + \lambda(s,A^2,B^2)} \quad (2)$$

and D is the missing mass of X. Thus, x_D is a good "direct fragmentation"

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scaling variable when the direct fragmentation process dominates and when the bombarding energy is high enough. We show in Fig. 1 the experimental data of Anderson, et al.[3] for the reaction $\alpha + {}^{12}C \rightarrow p+X$. As one observes, the experimental data scales with x_D when $x_D \gtrsim 0.20$ and $p_\alpha \gtrsim 1.74$ GeV/c/N, for different values of p_T. The analogous scaling variable x_D for target fragmentation can be obtained from Eqs. (1) and (2) by replacing $C_Z \rightarrow -C_Z$, $x_F \rightarrow |x_F|$ and interchanging $B_o \leftrightarrow A_o$, $B_Z \leftrightarrow -A_Z$. The experimental data[4] for backward proton production also scales well with x_D for target fragmentation.

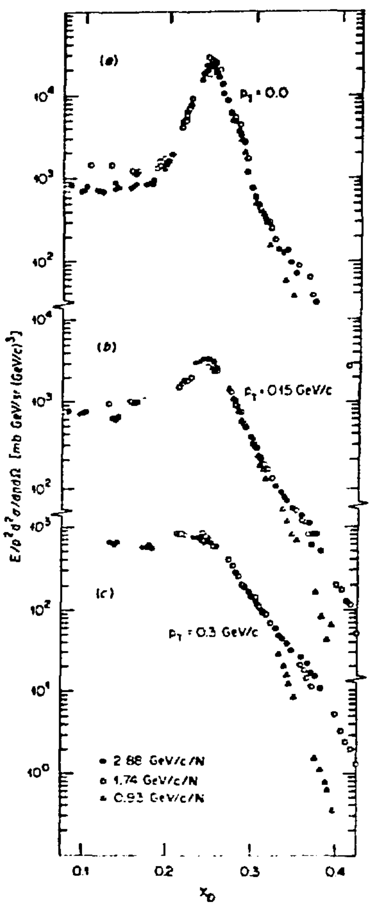

Fig. 1. Experimental invariant cross section for $\alpha + {}^{12}C \rightarrow p+X$. Data are from Ref. 3.

In the hard-scattering process, the target A and projectile B emit subsystems a and b which scatter to produce particle C via the basic process $a+b \rightarrow C+d$. Upon examining the six-fold hard-scattering integral,[2] one finds that for projectile fragmentation the integral depends predominantly on the variable

$$x_H = \frac{\gamma^2 + \sqrt{\gamma^4 - b^2(u' + C_T^2)}}{u' + C_T^2} \left[\frac{m_a(A_o + A_Z)}{m_A(B_o + B_Z)} - x_D \right] \qquad (3)$$

where

$$\gamma^2 = \tfrac{1}{2}[d^2 - a^2 - u'] \qquad (4)$$

and

$$u' = (m_a A/m_A - C)^2. \qquad (5)$$

For target fragmentation, the corresponding variable is obtained by replacing $C_Z \rightarrow -C_Z$, and interchanging $a \leftrightarrow b$, $A_o \leftrightarrow B_o$, $A_Z \leftrightarrow -B_Z$.

As a pion is not a normal constituent of a nucleus, we consider pions to be produced only by the hard-scattering mechanism. The experimental data should scale with the "hard-scattering" scaling variable x_H. Indeed, when the data of $p + Cu \rightarrow p+X$ (180°) are plotted with respect to x_H, we see that the experimental data scales well with x_H (Fig. 2), in contrast to the absence of scaling with respect to x_F observed earlier.[5,6] For forward pion production, the experimental data of $\alpha + {}^{12}C \rightarrow \pi^- + X$ also scale with x_H. In this case, x_H is approximately equal to x_F in the region of interest and thus there is also x_F scaling for forward pion production.[1]

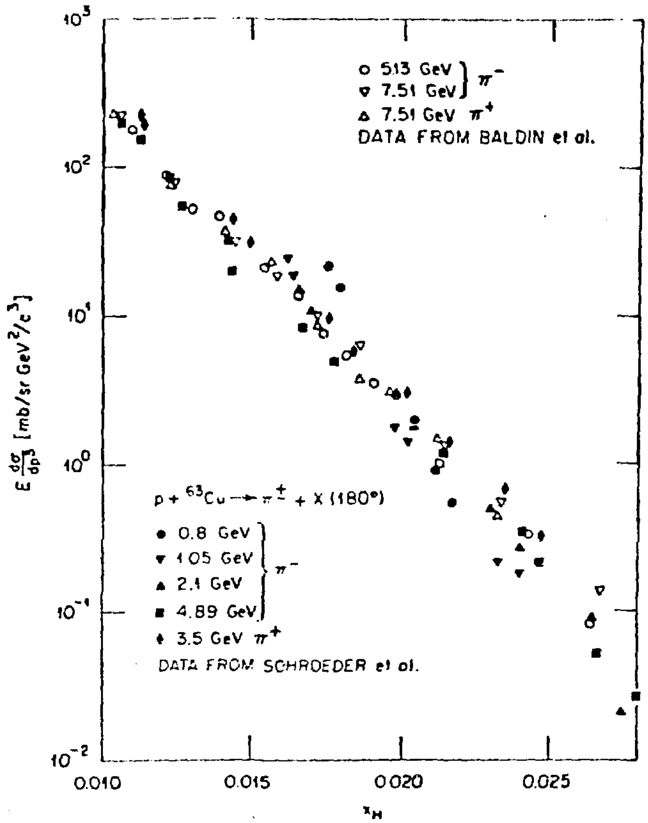

Fig. 2. Experimental invariant cross section for $p + Cu \rightarrow \pi^{\pm}+X$ (180°). Data are from Refs. 5 and 7.

In proton production the hard-scattering process becomes more important as $p_T >> 0.1$ GeV/c. However, in this case $x_H \simeq x_D$, and hence, x_D scaling persists even for large values of x_D as we observe in Fig. 2.

It is easy to show that in the projectile fragmentation region, x_D and x_H approaches x_F when $s >> D^2 - A^2$ and in the target fragmentation when $s >> D^2 - B^2$. We see that x_D and x_H are simple generalizations of x_F for the case when the rest masses are not small compared to s.

In conclusion, we have obtained scaling variables which allow the experimental data to scale properly for proton and pion production at the forward and backward angles. Their introduction also clarifies the underlying physics of the scaling phenomenon in nucleus-nucleus collision.

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