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PARTICLE PRODUCTION AT LARGE TRANSVERSE MOMENTUM IN NUCLEUS-NUCLEUS COLLISIONS*

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ABSTRACT

Based on a multiple hard scattering picture we derived simple relations between inclusive cross sections for large transverse momentum particle production in nucleus-nucleus, nucleon-nucleus and nucleon-nucleon scatterings. The relations are compared with the recent data for π^0 production in $\alpha\alpha$ collisions at high energy.

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Nucleus-nucleus collisions have recently attracted a fair amount of attention, subsequent to the measurements made by several experimental groups on $\alpha\alpha$ collisions at the CERN-ISR. Preliminary data on elastic scattering and particle production at both low and large transverse momentum have become available.[1-3] The fact that for the first time they are for relatively high energy (the beams were accelerated to the maximum momentum 31.5 GeV/c per charge) makes them particularly interesting. Here, we concentrate on inclusive hadronic cross sections at large-p_T.

If two nuclei (with nucleon numbers A_1 and A_2) collide, it is intuitively plausible that one can deduce a great deal about the resulting hadronic production from a knowledge of nucleon-nucleon (NN) and nucleon-nucleus (NA) collisions. In this note, we derive simple formulas [Eqs. (2) and (5)] which relate the single particle inclusive cross sections at large-p_T in A_1A_2, NN and $NA_{1,2}$ collisions. Our derivation is made using a multiple hard scattering picture,[4-6] since it is widely believed to be the cause for the anomalous nuclear enhancement[7] seen in hadron-nucleus collisions. However, as discussed later, it is quite possible that our relation is quite general and relatively model-independent. Before proceeding to the derivation, let us consider the special case of current experimental interest, namely $\alpha\alpha$ collisions and π^o measurements at large-p_T at 90^o in the nucleon-nucleon CM frame. For this case, our result reduces to a particularly simple form

$$I_{\alpha\alpha} = 8\left(I_{p\alpha} - 2I_{pp}\right) \qquad (1)$$

where I denotes the inclusive π^o cross section $E\,d\sigma/d^3p$ measured in all processes at the same nucleon-nucleon CM energy and at a CM scattering angle of 90^o. Equation (1) is in reasonable agreement with available preliminary data (see Fig. 1) and will be discussed later.

For a general nucleus-nucleus collision, the result for π^o production at 90^o in the nucleon-nucleon CM frame is

$$I_{A_1A_2} = A_1 I_{pA_2} + A_2 I_{pA_1} - A_1 A_2 I_{pp} \quad . \tag{2}$$

In order to have the same nucleon-nucleon CM energy $\sqrt{S}$, the CM energy for the pA interaction must be $\sqrt{SA}$ and that for the A_1A_2 interaction must be $\sqrt{SA_1A_2}$.

The derivation of Eq. (2) is easiest at the nucleon level. Consider a proton-nucleus collision. Since we are looking for produced π^o particles, neutrons and protons need not be distinguished. Therefore, in a multiple hard scattering formalism, the π^o can come from hard scattering in a single nucleon-nucleon interaction (whose cross section is I_{pp}) or from hard scatterings initiated by a simple nucleon in the beam (target) with several nucleons in the target (beam) nucleus. For two scatterings, the cross section is proportional to $A^{4/3}$. Thus, if more than two scatterings are ignored for the moment, we have

$$I_{pA} = AI_{pp} + A^{4/3} I_D \tag{3}$$

where I_D is a convolution of two hard scattering cross sections times appropriate nuclear factors (see Refs. 4-6 for details). By similar reasoning for a general nucleus-nucleus collision, one readily gets

$$I_{A_1A_2} = A_1 A_2 I_{pp} + \left(A_1A_2^{4/3} + A_2A_1^{4/3}\right) I_D \quad . \tag{4}$$

The term $A_1A_2^{4/3}$ $(A_2A_1^{4/3})$ corresponds to interactions of any nucleon in nucleus A_1 (A_2) with two nucleons in nucleus A_2 (A_1). Eliminating the model-dependent quantity $A^{4/3}I_D$ from Eqs. (3) and (4) yields Eq. (2).

In the above derivation, the effects of absorption and the possibility of having hard scattering of any nucleon from more than two nucleons has been neglected. These effects are probably small[4] and can be incorporated in a simple phenomenological manner by writing $A^{n_{eff}}$ I_D^{eff} instead of $A^{4/3}I_D$ in Eqs. (3) and (4). Of course, this change does not alter the subsequent derivation of Eq. (2).

Note, however, that in writing Eq. (4), we have implicitly neglected the possibility of more than one nucleon from nucleus A_1 (A_2) interacting with more than one nucleon from nucleus A_2 (A_1). As we are pointing out later on, this point may require re-evaluation if substantial deviations from Eq. (2) are experimentally observed.

Equation (2) is valid not only for π^o production, but also for any combination of particles which (by isospin) are produced with equal probability from both protons and nuetrons, for example η^o, $\pi^+ + \pi^-$, etc. However, if one looks at the production of a hadron which is preferentially produced off either protons or neutrons, it requires a little more effort to generalize Eq. (2). For the collision of nucleus (Z_1,N_1) containing Z_1 protons and N_1 neutrons with another nucleus (Z_2,N_2), our result is

$$\begin{aligned} I_{Z_1N_1,Z_2N_2} &= Z_1 I_{pA_2} + N_1 I_{nA_2} + Z_2 I_{pA_1} + N_2 I_{nA_1} \\ &\quad - \left[Z_1 Z_2 I_{pp} + N_1 N_2 I_{nn} + \left(Z_1 N_2 + Z_2 N_1 \right) I_{pn} \right] . \qquad (5) \end{aligned}$$

The new ingredients involved are the inclusive cross sections I_{nA}, I_{nn}, I_{pn} for neutron beams and/or targets. Like Eq. (2), Eq. (5) is also valid when all processes have the same nucleon-nucleon CM energy and a CM scattering of 90^o. Of course, Eqs. (2) and (5) can be extended to arbitrary values of the scattering angle in a straightforward manner.

It is worthwhile noting that the derivation of Eqs. (2) and (5) was completely carried out at the nucleons level -- that is, the nucleus was treated as a collection of nucleons without specific reference to further partonic substructure. Of course, it is hard scattering of partons which is responsible for large-p_T production. However, the details of the scattering involved do not show up explicitly in Eqs. (2) and (5), since they are burried in I_{pp}, I_{pA}, etc. Thus, to a large extent, our results are model-independent. In particular, the intriguing QCD-motivated idea that the nucleus is effectively a gluon filter[5] is also true for nucleus-nucleus collisions. This statement is of potential experimental interest for studying gluon jets due to the much larger cross sections in A_1A_2 interactions.

References 1 and 2 give a review of preliminary data on large-p_T π^o production in $\alpha\alpha$ collisions. The ratio of inclusive cross sections $R \equiv I_{\alpha\alpha}/I_{pp}$ is shown in Fig. 1.[8] In order to compare our theoretical expectations [Eq. (1)] with data, we need the ratio $I_{p\alpha}/I_{pp}$. Unfortunately, this ratio is not directly available at 90^o in the nucleon-nucleon CM frame. So, we shall make use of previous measurements on proton-nucleus collisions, which can be summarized by

$$\frac{I_{pA}}{I_{pp}} = A^{\alpha(p_T)} \quad , \quad \alpha(p_T) \equiv 1 + \delta(p_T) \quad . \tag{6}$$

The anomalous nuclear enhancement exponent $\alpha(p_T)$ is relatively energy-independent and has been measured for a variety of trigger particles.[7] Combining Eqs. (1) and (6), we get for $\alpha\alpha$ collisions:

$$R \equiv \frac{I_{\alpha\alpha}}{I_{pp}} = 16 \cdot \left(2 \cdot 4^{\delta(p_T)} - 1 \right) \quad . \tag{7}$$

This theoretical prediction for R is plotted on Fig. 1, with value of $\delta(p_T)$ for pions taken from Ref. (7). In general, the agreement with data is not bad, one should notice, however, that the data does tend to be higher at larger values of p_T. For π^o production in a general A_1A_2 collision, the enhancement is of the form

$$R \equiv \frac{I_{A_1A_2}}{I_{pp}} = A_1A_2 \left[A_1^{\delta(p_T)} + A_2^{\delta(p_T)} - 1 \right] . \tag{8}$$

Such a simple result is not valid for soft (low -- p_T) particle production where the relations between $I_{A_1A_2}$, $I_{NA_{1,2}}$ and I_{NN} are nonlinear.[9] It is only for the cross sections, or -- more precisely -- for the products of cross sections times nuclear thickness being small enough that these relations become effectively linear and then solvable in the manner presented above.

If the final data in Fig. 1 remains for large-p_T above the theoretical expectation, this could be due to hard scattering involving several nucleons in both colliding nuclei, and an eventual final state recombination into the observed π^o. Such a process, if present, will be most noticeable at larger p_T values, near the edge of phase space for nucleon-nucleon scattering. In a sense, one could even argue that, for p_T approaching the largest values normally available in the nucleon-

nucleon scattering, the ratio R has to ultimately become very large. We know of at least two examples of such phenomena: the hadronic jet production in hadron-nucleus scattering at large p_T (Ref. 6) and the so called "cumulative effect" in nucleus-nucleus scattering.[10] In both cases the detail explanation, although based on the same kinematical observation that the phase space for hadron-nucleus and nucleus-nucleus scattering need not be the same as in hadron-nucleon process, is rather model dependent. Similar explanation in our case would require much better and consistent data.

In any case, our Eqs. (2) and (5) provide a general, useful benchmark for nucleus-nucleus collisions based on current ideas of large-p_T particle production. If substantial deviations are experimentally observed in the future, they would clearly signal new physics. This could imply additional types of interaction mechanisms (like the one discussed in the previous paragraph) or possibly the conjectured new quark-gluon phase of matter.[11]

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REFERENCES

† Permanent address: Institute of Nuclear Research, 00-681 Warsaw, Poland.

1. M. Jacob, in Proceedings of the 5th High Energy Heavy Ion Study, Lawrence Radiation Laboratory, May 1981.

2. M. Faesler, in Proceedings of the International Conference on Physics in Collision, Blacksburg, VA, May 1981, and CERN preprint EP/81-103.

3. A. Karabarbournis et al., Phys. Lett. 104B, 75 (1981).

4. J. Pumplin and E. Yen, Phys. Rev. D11, 1812 (1975); P. M. Fishbane and J. S. Trefil, Phys. Rev. D12, 2113 (1975); P. V. Landshoff, J. C. Polkinghorne and D. M. Scott, Phys. Rev. D12, 3738 (1975); J. Kühn, Phys. Rev. D13, 2948 (1976); P. M. Fishbane, J. K. Kotsonis and J. S. Trefil, Phys. Rev. D16, 122 (1977); C. Michael and D. M. Webber, Phys. Lett. 83B, 243 (1979); V. V. Zmushko, Yad. Fiz. 32, 246 (1980) [Sov. J. Nucl. Phys. 32, 127 (1980)].

5. A. Krzywicki, J. Engels, B. Petersson and U. Sukhatme, Phys. Lett. 85B, 407 (1979).

6. F. Takagi, Phys. Rev. Lett. 43, 1296 (1979); D. Treleani and G. Wilk, Nuovo Cimento 60A, 201 (1980); V. V. Zmushko, Yad. Fiz. 32, 448 (1980) [Sov. J. Nucl. Phys. 32, 231 (1980).]

7. D. Antreasyan et al., Phys. Rev. D19, 764 (1979); C. Bromberg et al., Phys. Rev. Lett. 42, 1202 (1979) and Nucl. Phys. B171, 1 and 38 (1980).

8. References 1 and 2 do not agree about the data points from Experiment R110. In Fig. 1, we have plotted the results quoted by Jacob (Ref. 1). The results presented in Ref. 2 grow rather dramatically with p_T, reaching $R = 50$ for $p_T = 7$ GeV/c. Should this trend remain in the final data all our cautious remarks and suggestions would deserve further examination. We are indebted to T. J. M. Symons for remarks on this point.

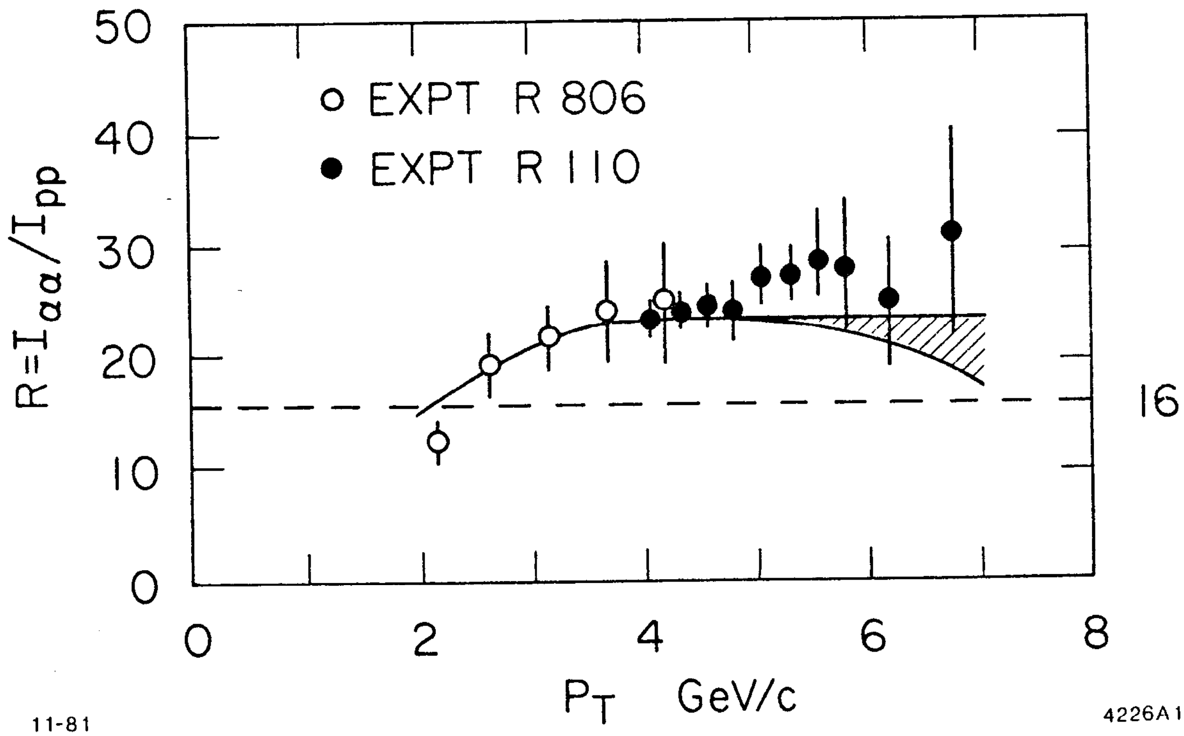
9. A. Białas and W. Czyż, "Quark model and nucleus-nucleus collisions of high energies," invited talk given at the Workshop on Future Experiments with High Energy Heavy Ions, Darmstadt, October 1980, Report INP-1114/PH and TPJU-12/80; G. A. Winbow, Phys. Rev. Lett. 40, 619 (1978); D. R. Harrington, Nucl. Phys. A314, 454 (1979); K. Kinoshita, A. Minaka and H. Sumiyoshi, Z. Phys. C8, 205 (1981).

10. A. M. Baldin et al., Sov. J. Nucl. Phys. 18, 41 (1979). For more details and references see: I. A. Schmidt and R. Blankenbecler, Phys. Rev. D15, 3371 (1977); S. J. Brodsky, in Proceedings of the First Workshop on Ultra-Relativistic Nuclear Collisions, Berkeley, California, May 21-24, 1979, p. 419, and SLAC-PUB-2395 (Sept. 1979).

11. See for example, L. McLerran, Proceedings of the EPS International Conference on High Energy Physics, Lisbon (1981); W. Willis, ibid., and CERN-EP/81-120 (Sept. 1981).

FIGURE CAPTION

Fig. 1. The ratio $R = I_{\alpha\alpha}/I_{pp}$ for π^o production at 90^o in the nucleon-nucleon CM frame as measured by experiment R806 (Athens-Brookhaven-CERN) and by experiment R110 (CERN-Oxford-Rockefeller).[8] Our predictions [based on Eqs. (1) and (7)] correspond to the shaded band which reflects the error bars of $\delta(p_T)$.[7] (The dashed line shows the naively expected result R = 16.)



50
40
30
20
10
0
R=$I_{\alpha\alpha}/I_{pp}$
○ EXPT R 806
● EXPT R 110
16
0
2
4
6
8
P_T GeV/c
11-81
4226A1

Fig. 1