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Emission of large-p_T particles in p-nucleus and nucleus-nucleus collisions

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Abstract. The observed dependence of the yield of high p_T particles on the atomic number A of the target and the incident energy, in p-α, α-α and p-nucleus collisions, is explained in a coherent tube model.

Keywords. High p_T particles; proton-nucleus; nucleus-nucleus collision.

1. Introduction

Large p_T reactions have been studied extensively (Jacob and Landschoff 1978; Antreasyn *et al* 1979; Cronin *et al* 1975; Bromberg *et al* 1979) using both nucleons and heavy nuclei as targets. The latter, however, have been used until quite recently more for convenience rather than for any particular merit in their use to yield new physics of intrinsic value. Now there has come a shift in our understanding of the importance of p-nucleus and nucleus-nucleus collisions due to two factors. Firstly, the few existing results in such collisions have shown rather anomalous features (Bromberg *et al* 1979). Secondly there have been several speculations (Domokos and Goldman 1981; Anishetty *et al* 1980) about the production of exotic forms of nuclear matter or dense quark-gluon plasmas in heavy ion collisions at highly relativistic energies and a possible similarity of these states with conditions that existed during the first few seconds after the 'big bang' which created the universe.

The purpose of this paper is to present a model for large p_T reactions involving heavy nuclei and to explain the data on p-nucleus collisions at Fermilab (Antreasyn *et al* 1979; Cronin *et al* 1975) and the recent ISR data (Karabarbounis *et al* 1981; Bell *et al* 1982; Angelis *et al* 1982) on p-α and α-α collisions. A gratifying feature of the model is that experimental results which look anomalous or mutually conflicting are seen to be, in fact, consistent with the model and that the differences are due to different kinematical situations.

2. Description of the model

The model discussed here is an elaboration of the model, proposed by Fredriksson (1976) to explain the data of Chicago-Princeton collaboration (CP) (Antreasyn *et al*

1979) on p-nucleus collisions. The essential idea of the model is that in a p-nucleus collision, a large fraction of the target nucleons, lying in a tube along the straight line path of the projectile through the target nucleus, acts collectively and coherently in the interaction. An immediate conseqence of this assumption is that the N-N C. M. energy $\sqrt{s}$ gets enhanced to an effective value $(s_{\text{eff}})^{\frac{1}{2}} = (\nu(A)\, s)^{\frac{1}{2}}$, where $\nu(A)$ is the average number of nucleons in the tube which interact collectively. The model is often referred to as a coherent tube model (CTM) (Bergstrom *et al* 1983). Narayan and Sarma (1964) had invoked the model several years ago to explain the features of deuteron production in 25 GeV P-A collisions.

All the struck nucleons in the tube presumably form a localized hot-dense quark-gluon composite which interacts with the projectile. It is assumed that the composite remains in the environment of the residual nucleus (nucleons outside the tube) during hadronization. A consequence of this assumption is that the particles, emitted at large angles and hence with large p_T, can undergo secondary collisions in traversing nuclear matter and suffer an attenuation in the yield of particles at higher p_T values. This consideration is particularly important in the CP experiments where the targets are relatively heavy nuclei and the particles are detected at 90° in the C. M. system. In ISR experiments, the internuclear cascade would be negligible as the nuclei are light α-particles.

3. p-nucleus collisions

To implement the CTM for p-nucleus collisions, we need to make two changes in relation to p-p collisions. One expects that p-nucleus cross-section would be larger than the p-p cross-section by a factor like A^{δ}, with a 'geometrical' value of $\delta \sim 2/3$. So we first multiply the p-p cross-section by a factor A^{δ}. Secondly the N-N C. M. energy $\sqrt{s}$ is replaced, as mentioned earlier, by $(s_{\text{eff}})^{\frac{1}{2}}$. These changes can be made in the conventional formulation of any model for large p_T reactions. In the present work, we merely use a parametrized form of the inclusive large p_T cross-sections and make the necessary changes, as was done by Fredriksson (1976).

The large p_T inclusive cross-sections for $p + N \rightarrow \pi^- + X$ have been parametrized (Busser *et al* 1973) as

$$\Sigma\,(pp) \equiv E\,(d\,\sigma\,(pp)/d^3\,p) = (K/p_T^n)\,\exp\,(-\,Bp_T/\sqrt{s});\;\; B = 26. \tag{1}$$

In the light of our remarks, one can parametrize the inclusive p-nucleus collisions as

$$\Sigma\,(PA) = E\,(d\,\sigma\,(PA)/d^3\,p) = (K/p_T^n)\,A^{\delta}\,\exp\,[-\,Bp_T/(s_{\text{eff}})^{\frac{1}{2}}] \tag{2}$$

From (1) and (2), we have

$$R\,(PA) \equiv \Sigma\,(PA)/\Sigma\,(pp) = \exp\,\{\log A\,[\delta + B\,(p_T/\sqrt{s})\,f_1\,(A)]\}, \tag{3}$$

$$\Sigma\,(PA)/\Sigma\,(PA_0) = \exp\,\{\alpha_{\pi^-}\,(s, p_T)\,\log A\}, \tag{4}$$

where

$$\alpha_{\pi^-}(s, p_T) = \delta + (Bp_T/\sqrt{s}) f_1(A_0) + (Bp_T/\sqrt{s}) [f_1(A_0) - f_1(A)]$$

$$[\log A] [\log A_0/A]^{-1}, \qquad (5)$$

$$f_m = [\log A]^{-1} \{1 - [\nu(A)]^{-m/2}\}, \qquad (6)$$

one can write $\nu(A) = \lambda A^{1/3}$ where λ is a constant which is treated as a free parameter. In CTM, $\lambda = (r_{int}/r_N)^2$, where r_{int} is the 'interaction radius' and r_N is the 'radius' of the nucleon. The last term on the right side of (5) is an A-dependent correction to α_{π^-}, which is, as we shall see, quite small for most nuclei. From (5), one finds that $\alpha_{\pi^-}(s, p_T)$ increases linearly with p_T and decreases inversely as $\sqrt{s}$.

4. Nucleus-nucleus Collisions

To calculate the yield of large p_T particles in α-α collisions, we need to make an appropriate extension of our model to deal with collisions between heavy nuclei. One trivial change is that A^δ gets replaced by $A_1^\delta A_2^\delta$, where A_1 and A_2 are the nucleon numbers of the colliding nuclei. A new ingredient is the occurrence of tube-tube (t-t) collisions, *i.e.* the interactions between massive composites formed out of tubes, aligned opposite to each other in the target and the projectile. In a t-t collision, the available C. M. energy is further augmented to $(s_{eff})^{\frac{1}{2}} = [\nu(A_1)\nu(A_2)s]^{\frac{1}{2}}$. The other new ingredient is the occurrence of more than one t-t collision. To make an estimate of this number, we draw an analogy between the collision of two heavy nuclei and the collision between two bunches in a linear collider, by regarding a nucleus as a bunch. Due to differences in the dimensions and the densities involved, the former results in t-t interactions and the latter in particle-particle (P_a-P_a) interactions. The number of P_a-P_a interactions in a single head-on collision between two bunches would be $\Delta_B = n_1 n_2 \sigma / F$ where n_1 and n_2 are the numbers of particles in the two bunches, F is the cross section of a bunch and σ is the p_a-p_a cross-section. We formally take the same expression to give the number of t-t interactions. For a head-on collision between two identical nuclei, we take $n_1 = n_2 = A$ and $F = 4\pi r_N^2 A^{2/3}$, and $\sigma = \pi r_{int}^2$. For a collision which is not head-on, we have to find n_1, n_2 and F for a given impact parameter, find the number of t-t interactions and finally average its value over all impact parameters. One can show that for identical nuclei, the average number Δ_A of the t-t interactions is

$$\Delta_A = C\lambda A^{4/3} [1 - (8A)^{-1/3}]^{-2}, \qquad (7)$$

where C is a slowly varying function of A, $C \to 0{\cdot}165$ as $A \to \infty$. In individual events, the number of t-t interactions would have a Poisson distribution. The quantity of interest is not Δ_A but the average number N_A for events in which there has been at least one t-t interaction, which is needed to trigger the event. This number N_A is simply $N_A = \Delta_A / (1 - \exp(-\Delta_A))$. The number N_A enters as a multiplying factor in the inclusive cross-section for nucleus-nucleus collisions. Incorporating the new ingredients in the parametrization of the inclusive cross-section for nucleus-nucleus collisions, the ratio $R(AA)$ can be written as:

$$R(AA) = \Sigma(AA)/\Sigma(pp) = N_A \exp\{\log A[2\delta + B(p_T/\sqrt{s})]f_2(A)\}. \quad (8)$$

The Chicago-Princeton (CP) data (Antreasyn *et al* 1979) on $p+\text{nucleus}\to\pi^-(\bar{p})+X$ has been parametrized as in (4), where A_0 is the nucleon number of some reference target. A significant result of this parametrization is that the exponent α_h (p_T) is independent of A. Secondly, the values of α_h (p_T) are larger than unity for values of $p_T > 2$ GeV/c. The values of α_h versus p_T for π^- and $\bar{p}$ are shown in figure 1. For π^-, the value of α_{π^-} increases linearly with p_T upto $p_T{\sim}3$ GeV/c. For values of $p_T{>}3$ GeV/c, the rate of increase slows down until it actually decreases with p_T. On the other hand, the value of $\alpha_{\bar{p}}$ shows a continuous increase upto the highest measured value of $p_T{=}6{\cdot}15$ GeV/c. The ISR results (Karabarbounis *et al* 1981) on the reactions $p+\alpha\to\pi^0+X$ and $\alpha+\alpha\to\pi^0+X$ have been presented as the ratios $R(p\alpha)$ and $R(\alpha\alpha)$. The values of $R(p\alpha)$ and $R(\alpha\alpha)$ are shown in figure 2. One would expect that the values of $R(p\alpha)$ to be greater than 4 and those of $R(\alpha\alpha)$ to be greater than 16, in the light of CP data on the values of α. Surprisingly, the measured values of $R(p\alpha)$ are consistently less than 4 except at one point, while the values of $R(\alpha\alpha)$ are considerably greater than 16. If the observed values of $R_{\alpha\alpha}$ are parametrized as

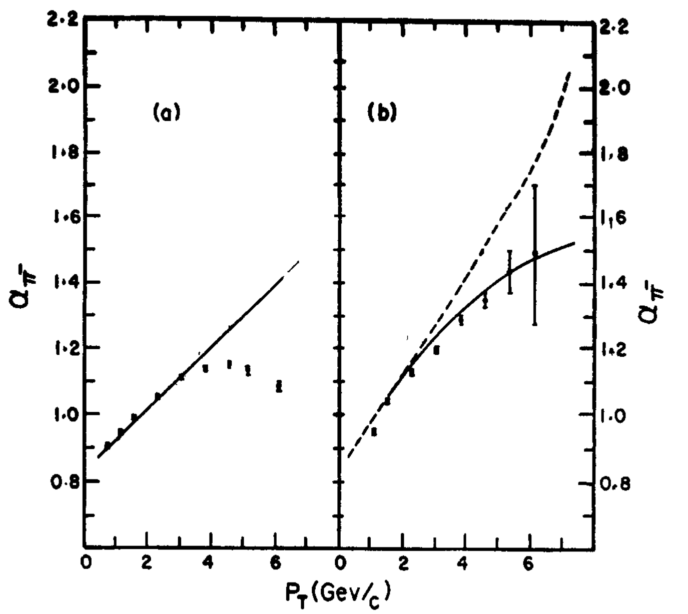

Figure 1. (a) α_{π^-} versus p_T for π^- at $E_L = 400$ GeV. (b) Same as in (a) for $\bar{p}$. Data from Anishetty *et al* (1980). Dashed and continuous curves: calculated values before and after correction.

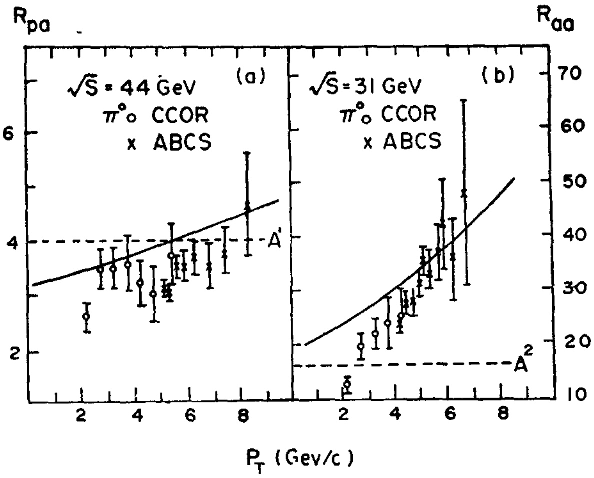

Figure 2. (a) $R(p\alpha)$ versus p_T. (b) $R(\alpha\alpha)$ versus p_T. Data from Karabarbounis *et al* (1981) and rapporteur talk by H G Fisher at the Int. Nat. Conf. on High Energy Physics, Lisloon 9-15 July 1981. Curves give predictions.

$(A_{\rm He})^{2\alpha_{\pi^0}}$, the value of α_{π^0} shows a linear increase with p_T, in apparent contradiction with CP data on π^-, but in agreement with the data on $\bar{p}$.

5. Comparison with experiment

The values of δ and λ in the present model, chosen to reproduce the initial linear rise of α_{π^-}, are δ=0·83 and λ=0·73. With these parameters, the values of α_{π^-} have been calculated for some typical nuclei at p_T = 3 GeV/c and lab-energy E_L = 400 ($s \simeq 2ME_L$), taking tungsten (as per CP data) as the reference nucleus. The calculated values of α_{π^-} for tungsten, titanium, aluminium and beryllium are 1·11, 1·08, 1·11 and 1·12 respectively. These values of α_{π^-} can be regarded as almost independent of A. The solid line in figure 1a shows the calculated values of α_{π^-} at lab-energy E_L = 400 GeV. The calculated values are in agreement with data for p_T< 3 GeV/c but in disagreement for p_T>3 GeV/c, as the experimental values start deviating from the predicted linear rise. One may be inclined to regard this discrepancy as a failure of the model but the recent ISR data brings in a see-saw change in the results which necessitates a closer examination of them *vis-a-vis* the model.

The decrease of α_{π^-} (p_T) at higher p_T values in the Fermilab experiment shows that the pions at higher p_T values are attenuated relative to the pions at lower p_T values. But the same thing does not happen for π^0 in the ISR experiment. A meaningful way (there does not seem to be any other) by which one can understand the attenuation of π^- and lack of attenuation for π^0, is to postulate that particles created in primary collisions inside a heavy nucleus, as in the Fermilab experiment, undergo secondary interactions and suffer an attenuation at higher p_T values. The absence of attenuation in the ISR experiment is explained as due to the lack of any significant internuclear cascade in p-α and α-α collisions. But we have a problem in regard to $\bar{p}$ for which

$\alpha_{\bar{p}}(p_T)$ does not show a decrease at high p_T values, even though the measurements were made with the same set-up as for π^-. We argue that this is due to an extra feature present in the case of $\bar{p}$ but not π^-. It is known experimentally that there is a strong threshold effect in the production of $\bar{p}$ as a function of the C. M. energy. In the context of CTM, the effective $(S_{\text{eff}})^{\frac{1}{2}}$, which is larger than the actual $\sqrt{S}$ lifts the C. M. energy into the range where the threshold effects become important. This results in an enhancement in the yield of high p_T antiprotons, which compensates more than the attenuation due to secondary collisions. It is interesting to note that the general trend of $\alpha_{K^-}(p_T)$ for K^- particles, which are created particles as π^- and which exhibit a mild threshold effect, is similar to that of $\bar{p}$.

6. Effect of Inter-nuclear cascade

In the absence of a realistic treatment of the inter-nuclear cascade, we intend to proceed heuristically and try to show a consistency in the behaviour of $\alpha_{\pi^-}(p_T)$ and $\alpha_{\bar{p}}(p_T)$ by invoking both attenuation due to secondary collisions and an enhancement due to threshold effects. Since there is no threshold in the production of pions (at these energies), we may take the degree of attenuation for π^- as simply the amount of deviation from the predicted linear rise. In the case of $\bar{p}$, both attenuation and enhancement are present. We can calculate the amount of enhancement in our model but one does not know the attenuation. We assume that the degree of attenuation for particles of a given type is proportional to its inelastic cross-section on nucleons. We would then be able to obtain $\alpha_{\bar{p}}(p_T)$ using the data on $\alpha_{\pi^-}(p_T)$.

According to the CP data (Antreasyn *et al* 1979), the ratio of $\bar{p}$ to π^- in p-p collisions and hence the ratio of their inclusive cross-sections, can be parametrized as

$$1/p_T^n\left(1-\frac{2p_T}{\sqrt{s}}\right)^b$$

with $n = 0{\cdot}27 \pm 1{\cdot}7$ and $b = 4{\cdot}29 \pm 1{\cdot}9$. Using this information the $\bar{p}$ inclusive cross-section in p-A collisions can be parametrized as (normalization to a proton target, this differs only slightly from the original normalization)

$$\Sigma(P + A \rightarrow \bar{p} + X)/\Sigma(P + P \rightarrow \bar{p} + X) = \exp\,[\alpha_{\bar{p}}(s,p_T)\,\log A], \tag{9}$$

where

$$\alpha_{\bar{p}}(s, p_T) = \alpha_{\pi^-}(s, p_T) + \frac{b}{\log A}\log\frac{\zeta - v}{\zeta\,(1-v)}, \tag{10}$$

$$v = 2p_T/\sqrt{s} \text{ and } \zeta = \sqrt{(\lambda A^{1/3})}.$$

Taking $b=6$, which is consistent with experiment, we calculate $\alpha_{\bar{p}}$ according to (10). The calculated values are shown in figure 1b as a dotted curve. This curve has to be corrected for attenuation. To this end, we define an 'attenuation factor' at each p_T value, which is the ratio of the calculated inclusive cross-sections before and after correction for attenuation. For π^-, the corrected value of α_{π^-} are identified with the experimental values. We assume, as stated earlier, that the ratio of the attenuation factors for π^- and p^- would be equal to the ratio of their inelastic cross-sections on nucleons. With this assumption, we have the relation

$$\alpha_{\bar{p}}^{\text{cal}} \rightarrow \alpha_{\bar{p}}^{\text{corr}} = \frac{\sigma_{\text{inel}}^{\bar{p}N}}{\sigma_{\text{inel}}^{\pi N}} \left(\alpha_{\pi^-}^{\text{cal}} - \alpha_{\pi^-}^{\text{expt}}\right),$$

where α^{cal} refer to values before attenuation. The values of $\alpha_{\bar{p}}^{\text{cal}}$, calculated in this manner, are shown in figure 1b. The corrected values are now in satisfactory agreement with experiment. The slight disagreement at two or three points can perhaps be improved by a better choice of the parameters. The present set of parameters have been chosen to get an over all agreement with results of p-nucleus as well as p-α and α-α collisions. As the results of p-α and α-α collisions have large errors and cannot be regarded as final, it would not be worthwhile to look for close agreement on one set of data.

7. Results on p — ∝ and ∝ — ∝ collisions

Coming to ISR results, the calculated values of $R(p\alpha)$ are shown by the curve in figure 2a. The calculated and experimental values agree within errors which are rather large. The unexpectedly small values of $R(p\alpha)$ are due to A_{He} ($A_{\text{He}} = 4$) being small and the equivalent lab-energy E_L ($S \sim 2ME_L$) being large, $E_L \sim 1000$ GeV. The curve in figure (2b) shows the calculated values of $R(\alpha\alpha)$ versus p_T according to (8). The calculated curve, besides being in agreement with data, reproduces the observed increase with p_T. The factors which cause $R(\alpha\alpha)$ to have a larger magnitude and a faster increase with p_T, in contrast to $R(p\alpha)$, are a lower value of E_L ($E_L \sim 512$ GeV) and the occurrence of t-t interactions. The model presented here is fairly well defined and it can be applied to any p-nucleus and nucleus-nucleus collision of equal or unequal masses. For instance, the model predicts that the ratio $R(AA)$ for the collision of two nitrogen ions at $p_T = 6$ GeV/c and a C. M. energy of 16 GeV per nucleon would be around 4000, a factor 20 larger than the naively expected value (14) while for aluminium the value of $R(AA)$ would be $\sim 2{\cdot}9 \times 10^4$ a factor 400 larger than (28).[2]

References

Angelis A L S *et al* 1982 CERN Preprint, CERN-EP/82-106

Anishetty R, Koehler P and Mc Lerran L 1980 *Phys. Rev.* **D22** 2793

Antreasyn D, Cronin J W, Frish H J, Schochet M J, Kluberg L, Pirone P A and Sumner R L 1979 *Phys. Rev.* **D19** 764

Bell B *et al* 1982 *Phys. Lett.* **B112** 271

Bergstrom L, Fredriksson S, Berlad G and Eilam G 1983 *Phys. Rep.* (to be published)
Bromberg C *et al* 1979 *Phys. Rev. Lett.* **42** 1202
Busser F W *et al* 1973 *Phys. Lett.* **B46** 471
Cronin J W, Frish H J, Schochet M J, Boymond J P, Pirone P A and Sumner R L 1975 *Phys. Rev.* **D11** 3105
Domokos G and Goldman J I 1981 *Phys. Rev.* **D23** 203
Fredriksson S 1976 *Nucl. Phys.* **B111** 167
Jacob M and Landshoff P V 1978 *Phys. Rev.* **C48** 285
Karabarbounis A *et al* 1981 *Phys. Lett.* **B104** 75
Narayan D S and Sarma K V L 1964 *Prog. Theor. Phys.* **31** 93