Two-temperature model for production of large-P_T particles

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A two-temperature model is proposed to explain the production of large-P_T particles in pp, p-nucleus, and nucleus-nucleus collisions. The model gives good fits to the data on pp and $p\bar{p}$ collisions over a range of c.m. energies $\sqrt{s}=23.5$ to 540 GeV, as well as $p\alpha$ and $\alpha\alpha$ collisions.

The production of large-P_T particles in hadron collisions has been studied extensively[1] to obtain information on the constituent structure of hadrons. The production of such particles is attributed to a hard scattering between two constituents, one from each of the incoming hadrons, followed by a fragmentation of the scattered constituents. While the model is reasonably successful[2] in reproducing single-particle inclusive cross sections, it has been less successful and more contrived[3] in fitting correlation data such as the distribution of particle momenta out of the trigger plane (P_{out}) components. To get agreement with such data, one has to introduce[2,3] average values of the "fragmentation P_T," which increase both with $\sqrt{s}$ and P_T of the trigger particle. The jet broadening observed by the UA2 collaboration[4] at $\sqrt{s}=540$ GeV indicates that the $\langle P_{\text{out}}\rangle$ components increase also on the "same side" of the trigger though this may not be so pronounced as on the "away side." While admittedly an initial hard scattering of the constituents can be the genesis of large-P_T processes, the mechanism of hadronization seems to be more complex than a simple fragmentation. (Though gluon bremsstrahlung leads to a broadening of jets, both theory and experiment need consideration of multigluon emission, which cannot be treated in a strict perturbative approach and becomes more of a model.) It is conceivably possible that the constituents after a hard scattering share their momenta with other constituents in their immediate neighborhoods, thereby creating excited clusters or blobs of quark-gluon matter at high temperatures. Motivated by such an idea, a two-temperature model has been proposed by Chew, Lee, Phua, and Liu[5] to explain the production of large-P_T particles in pp collisions. The model is extended here by incorporating the two-temperature concept to p-nucleus and nucleus-nucleus collisions in the context of a coherent tube approach.[6,7] The model is then applied to $p\alpha$ and $\alpha\alpha$ collisions, using the same parameters as in the two-temperature model for pp collisions. This extended two-temperature model is in agreement with the data on pp and $\bar{p}p$ collisions over a range of c.m. energies $\sqrt{s}=23.5$–540 GeV as well as the data on $p\alpha$ and $\alpha\alpha$ collisions. Though the model can, in principle, be applied to the collisions of protons on heavy nuclei, there is an extra complication, as noted by one of the authors,[6] due to a rescattering and attenuation of the secondaries in a heavy target nucleus. Except for this lacuna in the present formulation, the model provides a unified description of the production of large-P_T particles in the collisions of hadrons and all light nuclei with themselves or with one another. The success of the model would indicate that the two temperatures, which characterize the production of large-P_T particles, have some definite physical significance. We shall return later to this topic in relation to the current discussion on the existence of a deconfinement temperature and a phase transition between a hadron phase and a quark-gluon phase.

For pp and $p\bar{p}$ collisions, the single-particle (mostly pions, charged or neutral) inclusive cross section is written as

$$E\frac{d^3\sigma}{dp^3}=B_1e^{-P_T/kT_1}+B_2e^{-P_T/kT_2}\ , \tag{1}$$

where B_1 and B_2 are constants. The energy-dependent temperatures are parametrized as

$$\begin{aligned} kT_1&=a_1s^{1/4}\ \text{GeV}\ ,\\ kT_2&=a_2s^{1/8}\ \text{GeV}\ , \end{aligned} \tag{2}$$

where s is expressed in GeV^2. The constants B_1, B_2, a_1, and a_2 are treated as parameters in the model and are chosen to reproduce the data on pp and $\bar{p}p$ collisions. Their values[5] so obtained are

$$B_1=1.6\times10^{-31}\ \text{cm}^2c^3/\text{GeV}^2\ ,$$

$$B_2=8.0\times10^{-27}\ \text{cm}^2c^3/\text{GeV}^2\ ,$$

$$a_1=0.1194,\quad a_2=0.1378\ .$$

The cross sections for the production of large P_T pions have been calculated using the above parameters and compared with the experimental data[8–10] in Fig. 1 over a range of c.m. energies $\sqrt{s}=23.5$ to 540 GeV and P_T values from 2–12 GeV/c. Over this range, the two-temperature model gives consistently good fits to the data. Recently the UA2 collaboration[4] have presented data on the inclusive cross sections $d^2\sigma/dE_Td\eta$ (η=pseudorapidity) at $\sqrt{s}=540$ GeV in the P_T range 15–34 GeV/c. Due to certain cuts in the acceptance of the events, the measured cross sections do not represent the correct values. The authors estimate that the observed cross sections can be expected to be a factor 2–3 smaller than the actual values, besides an additional 30% uncertainty in the overall normalization. In an inset in Fig. 1, we have shown the data of UA2 collaboration, after converting them into invariant cross sections, and compared with the

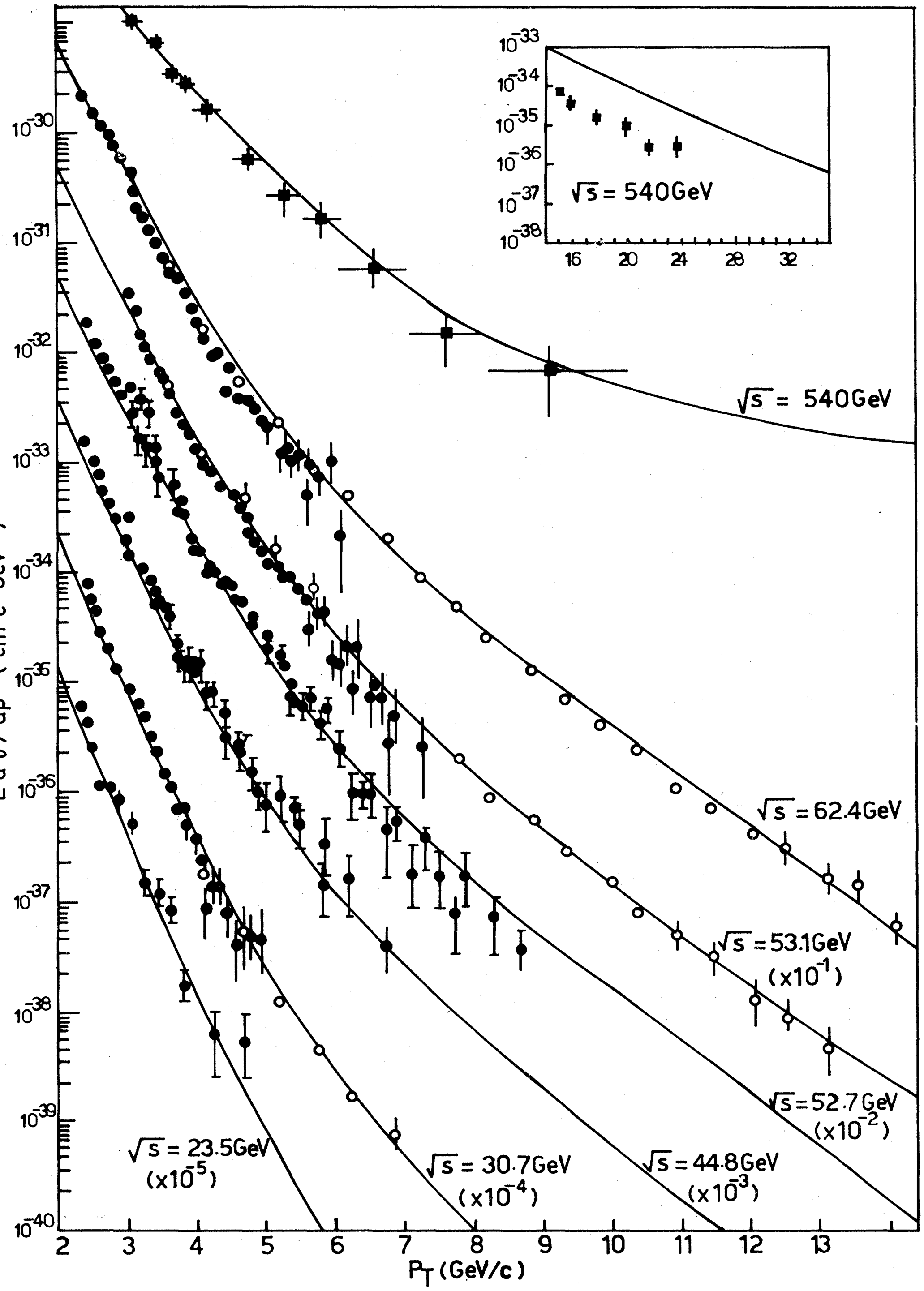

FIG. 1. The invariant cross section for π^0 as a function of P_T at different $\sqrt{s}$ values. Closed circles refer to the data of Ref. 9, open circles to the data of Ref. 8, and squares to the data of Ref. 10. The data in the inset are from Ref. 4. Solid curves are based on Eq. 1. A staggered scale is used (factors indicated in brackets) to avoid crowding of points.

two-temperature model. The parametrized values are larger than the experimental values; this cannot, however, be regarded as a disagreement with the parametrization, due to the uncertainties in the data. Our parametrization would indicate that the uncertainty in the data has a P_T dependence, besides an uncertainty in the normalization. There is urgent need for accurate data at values of $P_T > 15$ GeV/c in order to discriminate between a power law versus an exponential dependence of the cross sections.

The extension of the model to include p-nucleus and nucleus-nucleus collisions is made in the context of a coherent tube approach.[6,7] The essential idea in this approach 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, act collectively and coherently in the interaction. One may imagine that all the struck nucleons in the tube form a localized hot, dense composite which interacts with the projectile. An immediate consequence of this assumption is that the pp c.m. energy $\sqrt{s}$ gets enhanced to an effective value $\sqrt{s_A}=\sqrt{\nu(A)s}$, where A is the baryon number of the target and $\nu(A)$ is the average number of nucleons which interact collectively in the tube. One can write $\nu(A)=\lambda A^{1/3}$ where λ is a constant. In the coherent tube model $\lambda=(r_{\rm int}/r_N)^2$, where $r_{\rm int}$ is the "interaction radius" and r_N is the radius of the nucleon. Besides, one expects that the p-nucleus cross section would be larger than the pp cross section by a factor A^δ, where δ is taken to have its geometrical value $\frac{2}{3}$. With these changes, the large P_T inclusive cross section can be written as

$$P_0\frac{d^3\sigma_{pA\to h+x}}{dp^3}=A^\delta\left[B_1\exp\left[-\frac{P_T}{a_1(s_A)^{1/4}}\right]+B_2\exp\left[-\frac{P_T}{a_2(s_A)^{1/8}}\right]\right]. \tag{3}$$

The application of our model to nucleus-nucleus collisions is a simple extension of the logic employed for p-nucleus collisions. The concept of particle-tube interaction in a p-nucleus collision gets replaced by a tube-tube (t-t) interaction. In practical terms, this implies that the effective c.m. energy $(s_{A_1A_2})^{1/2}$ is equal to $(\nu(A_1)\nu(A_2)s)^{1/2}$, where A_1 and A_2 are the baryon numbers of the colliding nuclei. Another trivial change is to replace A^δ by $(A_1A_2)^\delta$. A new ingredient in a nucleus-nucleus collision is the occurrence of more than one t-t interaction in a collision. The average number of t-t interactions per collision is estimated by an analogy with the collision of two bunches in a collider by regarding a nucleus as a bunch. The differences in the dimensions and densities involved in the two cases is to change a particle-particle interaction in the collision of two bunches to a t-t interaction in the collision of two nuclei. Using this analogy, the number N_A of t-t interactions in the collision between identical nuclei of baryon number A has been estimated.[6] It is given by

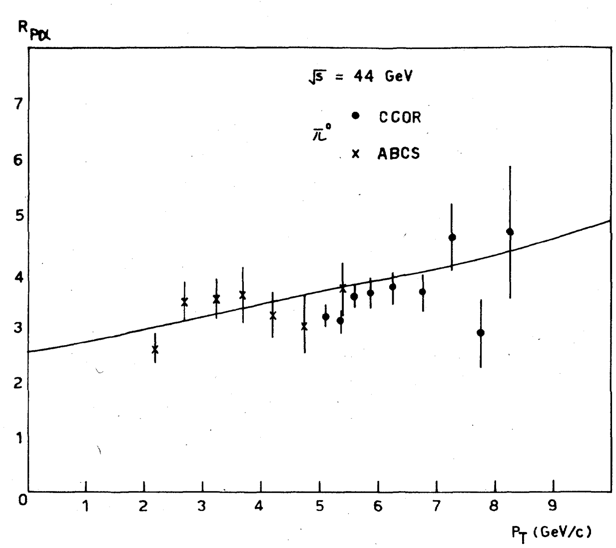

FIG. 2. Values of the cross-section ratio $R_{p\alpha}$ between $p\alpha$ and pp versus P_T. The curve gives the calculated values. The data are from Ref. 11.

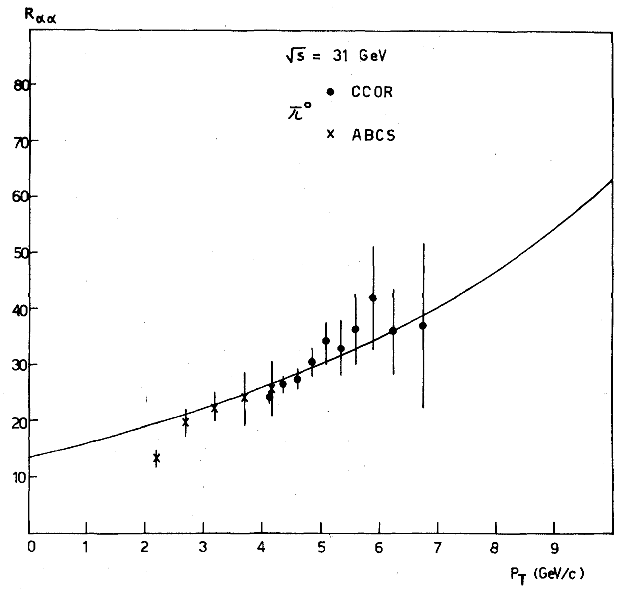

FIG. 3. Values of the cross-section ratio $R_{\alpha\alpha}$ between $\alpha\alpha$ and pp versus P_T. The curve gives the calculated values. The data are from Ref. 11.

$$N_A=\frac{\Delta_A}{1-\exp(-\Delta_A)}, \tag{4}$$

where

$$\Delta_A=C\lambda A^{4/3}[1-(8A)^{-1/3}]^{-2}. \tag{5}$$

Here Δ_A is the average number of t-t interactions, while N_A is the average over events in which there has been at least one t-t interaction which is needed to trigger the event and $C\sim0.165$ is a constant. Incorporating the relevant factors, the large P_T inclusive cross section for the collision of two identical nuclei is given by

$$P_0\frac{d^3\sigma}{dp^3}=N_Ae^{2\delta}\left[B_1\exp\left[-\frac{P_T}{a_1(s_{AA})^{1/4}}\right]+B_2\exp\left[-\frac{P_T}{a_2(s_{AA})^{1/8}}\right]\right]. \tag{6}$$

The only new parameter introduced in extending the two-temperature model to p-nucleus and nucleus-nucleus collisions is λ, which is chosen to have a value $\lambda=0.8$. The $p\alpha$ and $\alpha\alpha$ inclusive cross sections based on (3) and (6), respectively, are plotted in Figs. 2 and 3 as cross-section ratios $R_{p\alpha}$ between $p\alpha$ and pp collisions and $R_{\alpha\alpha}$ between $\alpha\alpha$ and pp collisions and compared with the CERN ISR data.[11] From the quality of the fits in Figs.

1–3, the model can be regarded as having a good measure of success in reproducing the data.

The main aim of this paper has been to highlight the two-temperature model to explain the production of large-P_T particles in hadron collisions, and to show that the model can be extended in a reasonable manner to nuclear collisions and that the results are in reasonable agreement with experiment.

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