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NEUTRAL PION PRODUCTION IN NUCLEUS-NUCLEUS COLLISIONS
AT 158 AND 200 GeV/NUCLEON

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INTRODUCTION

Two years ago, at the 12th Winter Workshop on Nuclear Dynamics held here in Snowbird, I presented WA80 limits on direct photon production in 200-GeV $^{32}\text{S}+\text{Au}$ collisions.¹ It was found that the results were consistent (within 1σ) with the absence of an excess of photons over those that can be accounted for by the two-photon decay branches of π^0 and η mesons and by the small photon contributions from other radiative decays. We are in the process of finalizing our direct-photon production results from collisions of lead nuclei at 158 GeV/nucleon. I will briefly discuss the status of the analysis and give some preliminary results at the end of this talk. However, most of this presentation is concerned with a very different aspect of our photon measurements: distributions of neutral pions. In contrast to direct photons which probe initial collision conditions, hadrons, such as neutral pions, interact strongly and decouple late in the reaction evolution and, thus, provide us with information concerning the system at freeze out. Transverse momentum spectra at low and intermediate p_T relate to thermodynamic and hydrodynamic descriptions of the hot, dense systems. In addition, the high- p_T region reflects the hard-scattering regime and may help us understand initial-state particle production by forming a bridge to proton-proton and proton-nucleus results. It follows that it is essential that the π^0 measurements cover a large p_T range.

INCLUSIVE π^0 EXPERIMENTAL RESULTS

Most of the data shown here are WA80 results from S+S and S+Au collisions at 200 GeV/nucleon² although some preliminary WA98 Pb+Pb data at 158 GeV/nucleon are also presented.^{3,4} The π^0 yield was obtained via the two-photon decay branch by means of invariant-mass reconstruction and by using the mixed-event technique to subtract the large combinatorial background.² Efficiency-corrected π^0 cross sections obtained in the rapidity range $2.1 < y < 2.9$ are shown as a function of the transverse mass, m_T , for S+S and S+Au reactions in Fig. 1. The data are presented for central, peripheral, and minimum bias (mb) trigger conditions. The central event class consists

of 7.7% of σ_{mb} in S+Au collisions, which corresponds to a complete overlap of the S projectiles with the Au target nuclei and to about 110 participating nucleons per collision. On the average, about 30 participating nucleons play a role in each of the 30% most peripheral events. The transverse mass spectra of Fig. 1 cover a range of 6-7 orders of magnitude and extend to 3-4 GeV/c. It can be seen in the figure that the spectra are not exponential over their entire range and, thus, cannot be fitted with a single exponential function. However, it is reasonable to attempt such fits in a limited m_T region, and exponential fits to the data with $d\sigma/dm_T^2 \propto \exp(m_T/T)$, limited to the region $0.8 \text{ GeV}/c \leq m_T \leq 2.0 \text{ GeV}/c$, are shown in Fig. 1, together with the corresponding values of the inverse slope parameters, T . Although the slope parameters are not identical to temperatures in the strict thermodynamic sense, it is nevertheless customary to use the two terms interchangeably. Note that higher apparent temperatures are attained in central collisions than in peripheral collisions.

Figure 1. Invariant cross sections of π^0 mesons from reactions of S+S (left) and S+Au (right) at 200 GeV/nucleon measured in the rapidity range $2.1 \leq y \leq 2.9$. The events are selected for centrality with the percentage of the minimum bias cross section as indicated. The solid and dashed lines represent exponential fits in the region $0.8 \text{ GeV}/c \leq m_T \leq 2.0 \text{ GeV}/c$ with slope parameters, T , as indicated. (See text.)

It is clear from the fits of Fig. 1 that the spectra are poorly described by exponential curves, even in a limited m_T range. The spectra exhibit an overall concave shape similar to those obtained from pp collisions. They are better described in terms of local slopes defined by

$$T_{loc}^{-1} = -\frac{d}{dm_T} \left[\log \left(E \frac{d^3 \sigma}{dp^3} \right) \right].$$

The above expression was used to determine individual values of T_{loc} locally using three adjacent data points of Fig. 1 for each value of T_{loc} . The results are shown for S+Au in Fig. 2 together with pp minimum bias data.^{5,6} As expected, the extracted local slopes

are not constant as would be the case for an exponential distribution. Instead, they are found to increase monotonically with increasing transverse mass. Except at the highest values of m_T where statistical errors are large, the local slopes of central events are systematically higher than those of peripheral collisions. The observed increase of the local slopes with increasing m_T is nearly linear, implying that two-parameter fits should adequately describe the m_T spectra of Fig. 1. Such fits have been implemented successfully and are discussed in Ref. 2.

Figure 2. Local slope values extracted for the S+Au system from the data of Fig. 1 as described in the text. Local slope values from pp minimum bias data^{5,6} are also shown. The dashed line represents a two-parameter fit to the pp local slope data. (See Ref. 2 for details.)

The pp slope parameters shown in Fig. 2 lie significantly below the nucleus-nucleus data and rise from about 150 MeV to about 220 MeV, indicating that the original m_T spectra must also exhibit a strongly concave shape. The fact that the local slopes obtained from heavy-ion reactions are systematically higher than those obtained from pp reactions may indicate that nontrivial collective effects play a role in particle production in nucleus-nucleus collisions.

DISCUSSION

In a thermalized system the hadron p_T spectra reflect the temperature of the system at the time of decoupling. The presence of collective motion, such as hydrodynamic flow, alters this idealized picture. As a consequence, the transverse velocities of particles are made up of a random thermal motion component and an ordered collective expansion velocity. Changes in these components from one reaction system to another will be reflected in the observed transverse momentum distributions. Deviations of these distributions from exponential behavior have to be understood in terms of spe-

cific effects. For example, the apparent "enhancement" at low values can, in many instances, be attributed to contributions from the decay of a large number of short-lived heavier resonances. On the other hand, it is possible that the same perturbative QCD effects that explain spectra from pp collisions above about 2 GeV are in part responsible for the observed flattening of the distributions in the high- p_T region. Thus, the "nuclear" effects observed in pA reactions have been considered in terms of multiple parton scattering. An extension of these calculations to nucleus-nucleus collisions is provided by the kinetic parton cascade model⁷ which treats large-momentum-transfer reactions on the basis of interacting quarks and gluons. However, this model applies strictly to high- p_T processes and only phenomenological models are available for the description of low- and medium- p_T processes.

We have compared our data to two of the most widely-used string-based phenomenological models, VENUS⁸ and FRITIOF⁹. These and similar models include nuclear geometry but otherwise treat nucleus-nucleus collisions as a superposition of nucleon-nucleon collisions, using experimental data from elementary collision processes as input. Any possible collective effects are neglected. Typical comparisons with a broad range of data indicate that the inherent extrapolations from pp collisions provide a reasonable description of nucleus-nucleus collisions, particularly in the medium- p_T range. However, deviations from standard string-model simulations are evident at both low and high p_T , particularly in the case of central events. To account for the deviations several model extensions have been introduced, including such mechanisms as hard-scattering processes,⁹ rescattering of the produced particles in the target nucleus and among themselves,⁸ production of quark clusters, and color-rope formation.

Figure 3 shows comparisons of data from central S + Au collisions at 200 A·GeV to calculated results obtained with VENUS 4.12 (Ref. 8) and with FRITIOF 7.02 (Ref. 9). The experimental acceptance was taken into account in the simulation process, and no normalization to the experimental cross section was made. For p_T values below about 1 GeV, agreement between measurements and calculations is reasonably good. Beyond 1 GeV, FRITIOF results fall substantially below the data, while VENUS calculations also deviate from the measurements but only beyond 2 GeV and in the opposite direction. (See inset of Fig. 3.) The good agreement up to 2 GeV between the data and VENUS simulations is attributed to the implementation of rescattering of produced particles in this model. Both calculations fail to reproduce the data at the highest p_T values.

A rather different approach makes use of nuclear hydrodynamics and treats the fireball created in a nucleus-nucleus collision as an expanding thermodynamical system characterized by a temperature, T , a chemical potential, μ , and an expansion velocity, β (Refs. 10-13). Comparisons to our S+Au and Pb+Pb data were made within the context of this model using a computer program provided by the authors of Ref. 13. Effects of the decay of short-lived heavier resonances and of transverse flow were included in the calculations. By fixing the baryonic chemical potential at the value of $\mu_b = 200$ MeV and by varying the temperature and expansion velocity, good fits to the experimental data were obtained. An example of such a calculation is shown in Fig. 4 for preliminary data from central Pb+Pb collisions at 158 GeV/nucleon.⁴ The best fit is obtained with $T = 164$ MeV and $\langle\beta\rangle = 0.25$. However, the T and β parameters are strongly correlated and a range of combinations of T and $\langle\beta\rangle$ adequately describes the data. The fits are not very sensitive to values of the baryonic chemical potential because pions from the decay of baryon resonances contribute primarily in the very low p_T range where there is no experimental coverage. This can be seen in Fig. 4 where the total yield is broken down into direct thermal pions (dashed line), the contribution from ρ decays (dotted line) and the contribution from all other resonances (dot-dashed

Figure 3. Comparison of the measured π^0 invariant yield per event as a function of the transverse momentum for central (7.7% of σ_{mb}) S+Au collisions at 200 GeV/nucleon to calculated distributions obtained from string models VENUS⁷ and FRITIOF.⁸ The experimental acceptance has been folded into the theoretical calculations. The inset shows the ratios of model predictions to measured results.

line). The ability of this thermodynamic model to describe the transverse momentum spectra of several systems over a large p_T range is impressive and suggests that collective effects play a significant role in nucleus-nucleus collisions even at these extreme energies.

Nix et al.¹⁴ have made recent calculations which are relevant to the thermodynamic analysis described above as well, as to several similar analyses. Nix and coworkers have used a nine-parameter expanding-source model that includes special relativity, quantum statistics, resonance decays, and freeze-out on a hypersurface in space-time to analyze preliminary NA44 π^+ , K^+ and K^- one-particle multiplicity distributions and π^+ and π^- two-particle correlations in central Pb+Pb collisions at 158 GeV/nucleon. They found the freeze-out temperature to be below 100 MeV and the longitudinal and transverse collective velocities (anticorrelated with the temperature) to be substantial. They proceeded to reconcile their findings with previous analyses of data from both the Pb+Pb reaction and from other systems in which much higher (120-140 MeV) freeze-out temperatures were found. They concluded that several approximations made in analyses with one of the versions¹¹ of the same thermodynamic model used in this work are responsible for the relatively high extracted temperatures. (For details, see Ref. 14.) It is not clear if in our own analysis, it is the same accumulation of effects

Figure 4. Preliminary transverse-mass distributions of neutral pions from central Pb+Pb collisions at 158 GeV/nucleon. The lines indicate various components calculated in a thermodynamic model in which resonance decays are taken into account.¹³ (See text.)

from several implicit approximations which results in extracted temperatures that are even higher than 120-140 MeV.

UPDATE ON DIRECT PHOTON PRODUCTION

Directly-radiated single photons have a low interaction probability and, consequently, will reflect the thermal properties of hot dense matter such as the quark-gluon plasma (QGP), a hadron gas, or a mixture of both. Thus, in principle, photons provide us with an excellent probe of the early stages of nucleus-nucleus collisions. This is what has motivated the WA80/WA93/WA98 Collaboration to put its primary emphasis on photon measurements. In practice, however, this “penetrating probe” is less than ideal. This is because the measurement of direct photons is difficult, since they are embedded in a very large background from the decay of π^0 mesons, and because a hot hadron gas is expected to radiate photons with emission rates that are similar to those that are expected from the QGP.

The WA80 Collaboration has deduced direct photon yields for $^{32}\text{S}+\text{Au}$ at 200 GeV/nucleon on a statistical basis, as a function of p_T , by comparing the total photon yield to that which can be attributed to all long-lived decays.¹⁵ The results, which are sensitive at the 5% level of inclusive photons, are consistent (within 1σ) with the

absence of photon excess in both central and peripheral collisions. In Ref. 15 upper limits on direct photon emission at the 90% confidence level were deduced for central collisions as a function of p_T . These upper limits are important in that they rule out the possibility that a high initial temperature may have been attained in the early phase of the collision.

More recently, the WA98 Collaboration has measured photons from Pb+Pb collisions at 158 GeV/nucleon. While the complicated direct-photon analysis of the data is not completed, preliminary results were shown at the recent Quark Matter '97 Conference.³ The analysis procedure follows closely that of Ref. 15. First, the invariant mass of all photon pairs measured in the lead-glass calorimeter (LEDA) is reconstructed. The mixed-event technique is then used to evaluate the combinatorial background. The π^0 and η yields are extracted and corrected for geometrical acceptance and reconstruction efficiency of the detector. The reconstruction efficiency is a function of particle multiplicity since at higher occupancy levels the probability of several particles hitting the same detector element increases. Data from the charged-particle veto located directly in front of LEDA are folded into the analysis. The direct-photon excess is then determined via the difference between the inclusive photon yield (measured simultaneously with the π^0 and η yields) and the calculated photon background contributions from decays of the measured π^0 and η yields with a small correction for other (much smaller) contributions from the decay of heavier resonances. Systematic errors are minimized by the use of the ratios $(\gamma/\pi^0)^{obs}$ and $(\gamma/\pi^0)^{bkgd}$. If an excess of photons is present, the ratio $\frac{(\gamma/\pi^0)^{obs}}{(\gamma/\pi^0)^{bkgd}}$ is greater than 1. Indications from the preliminary analysis are that there is, indeed, a small but significant excess of photons over the hadronic background in the medium- and high-transverse-momentum regions in central collisions. The results appear similar for peripheral collisions, but the excess is probably within systematic errors. Analysis by two WA98 groups working independently is continuing, and final results are expected soon.

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