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TITLE LOW P_T PHENOMENA OBSERVED IN HIGH ENERGY NUCLEAR COLLISIONS

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Low p_T phenomena observed in high energy nuclear collisions

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For several decades, experiments have reported an enhancement in the pion invariant cross section at low p_T (< 300 MeV/c) when compared to a thermal fit or minimum bias pp results. Experimental results from pp reactions at the ISR to heavy ion collisions at CERN will be reviewed then compared to extract trends. Several theoretical explanations will be discussed. An emphasis will be placed on the role of resonances and a comparison of data to models will be presented.

1. INTRODUCTION

An excess of pions at low p_T was first observed at the ISR when high multiplicity events from pp and $\alpha\alpha$ collisions were compared to minimum bias pp distributions [1]. Low p_T enhancement was later seen in cosmic ray data [2], pA (Fermilab, CERN) [3-6] and AA results (AGS, CERN) [5-12]. A list of experiments which have studied low p_T behavior are listed in Table 1.

Table 1
Experiments that have studied low p_T behavior

Experiment	Projectile	Target	Rapidity
CERN-Heidelberg-Lund (ISR) [1]	p, α	p, α	
Atwater et al., [2]	cosmic	Ag, Br	
Garbutt et al., (Fermilab) [4]	p	C, W	
Chaney et al., (Fermilab) [3]	n	Be, Al, Cu, Sn, Pb	
NA34 [5]	p,O,S	W	$1.0 < y < 1.9$
NA35 [6]	p,O,S	Au, S	$0.6 < y < 3.0$
EMU5 [24, 12]	S	Pb	$1.0 < y < 4.0$
NA44 [25, 11]	p, S	Pb	$3.1 < y < 4.1$
E810 [7]	Si	Au, Cu	$2.2 < y < 2.6$
E802/E859/E866 [9, 29, 30]	Si, Au	Au, Pb	$0.6 < y < 1.4$
E814 [8, 32, 31]	p,Si	Pb, Al	$2.8 < y < 3.6$

Several intriguing explanations have attempted to describe this behavior, including exotic behavior in dense hadronic matter [13-16] and the decay of quark matter droplets [17]. The excess of low p_T particles could also be a result of collective effects [2, 18] or a reflection of the dynamics of the hot collision zone in the reaction, such as baryonic and mesonic resonances [10, 19-21].

2. EXPERIMENTAL RESULTS

The CERN-Heidelberg-Lund Collaboration studied $\alpha\alpha$ and pp collisions at the ISR [1]. Where previous ISR experiments found that the inclusive cross sections either turned over or were well described by an exponential in m_T [22, 23], they observed an excess of low p_T particles with increasing muitiplicity when they compared high multiplicity to minimum bias events. This excess is small compared to that observed in pA and AA collisions and may be due to a different phenomenon. Low p_T enhancement was also seen in pA collisions at Fermilab [3, 4] and in high multiplicity cosmic rays in emulsion [2].

There are four CERN heavy ion experiments that have studied single hadron distributions at low p_T in a variety of rapidity ranges: NA34 [5], NA35 [6], EMU5 [24, 12], and NA44 [25, 11]. NA34 studied 200GeV/c central (high E_T) pA and AA collisions ($1.0 < y < 1.9$). At CERN, the mid-rapidity is at 3 and beam rapidity is at 6. The resulting negative hadron cross sections, corrected for electron contamination, are shown in figure 1; a parameterization of the minimum bias pp results are also included for comparison. The magnitude of the enhancement at low p_T in pA is similar to that observed in the AA collisions. Ratios of cross sections from various reactions indicate a weak dependence on projectile and no dependence on centrality in the rapidity range covered [5].

Figure 2 shows negative hadron spectra measured by NA35 in different rapidity regions; pAu data show a similar magnitude of enhancement [12, 6]. These data have been corrected for electron contamination. The low p_T behavior shows a dependence on rapidity [12]. New NA35 results also show a strong rapidity dependence and an enhancement in pA collisions [26].

EMU5 measures negative hadrons in the rapidity range of 1.0 to 4.0 and historically, has claimed no low p_T enhancement in their data [24]. However, when their data is plotted with NA35 results, one sees good agreement [12]. There exists a discrepancy between NA34 and EMU5 at the most backwards rapidity region of overlap which may be an indication of the rapidity dependence of the low p_T behavior. The NA34 low p_T acceptance is concentrated near rapidity of 1.0, while the EMU5 data are distributed within the 1.0-2.5 rapidity range [27].

NA44 measures identified pions in pA and AA collisions near mid-rapidity, eliminating electron contamination online with a gas cherenkov counter [25, 11]. Figure 3 shows pPb and pBe cross sections and the ratio pPb/pBe ($3.1 < y < 4.1$). A small enhancement is indicated at low p_T and is estimated to be < 7%. The SPb/pBe shows an enhancement similar in magnitude. NA44 observes no difference between the shapes of the π^+ and π^- distributions, no strong dependence on centrality, and no enhancement in kaon spectra at low p_T [11, 28].

There are three AGS experiments that have measured hadron spectra at low p_T. E810 measured negative hadrons in AA at 14.6GeV/c in the rapidity range of 2.2-2.6. At the AGS, mid-rapidity is ≈ 1.7 and beam rapidity is ≈ 3.4. The spectra are well described by a sum of two exponentials and they estimated that approximately 30% of the pions

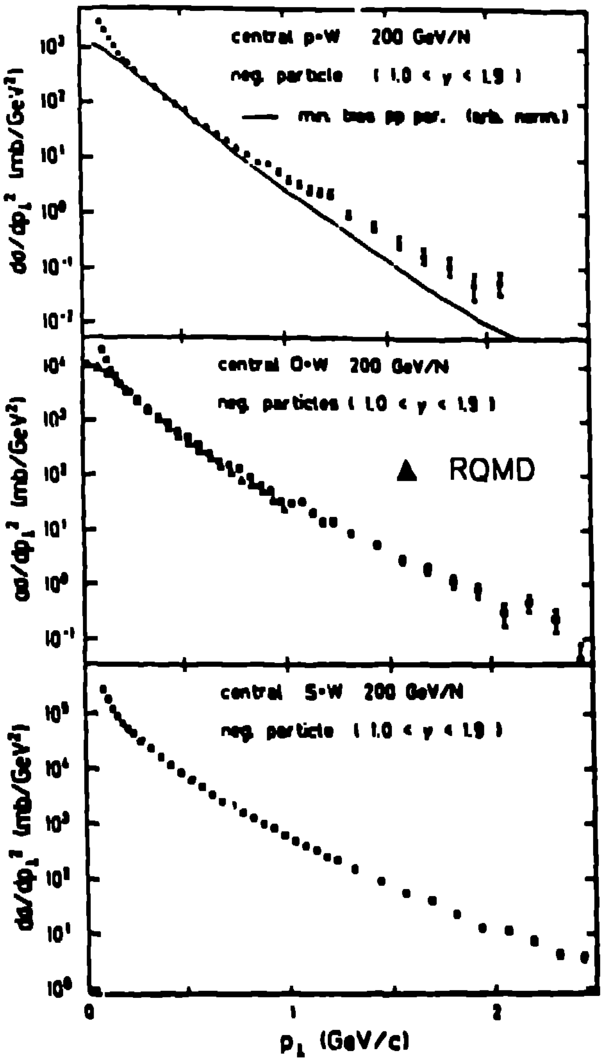

Figure 1. NA34 p_T spectra (reprinted [5]). RQMD calculations of O+Au ($1.0 < y < 1.9$) are included in the O+W plot.

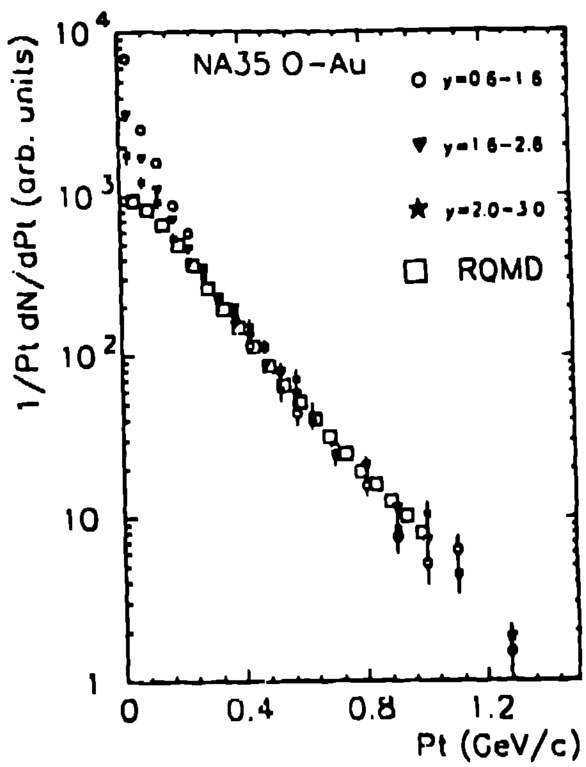

Figure 2. NA35 O+Au p_T spectra (reprinted [12]). RQMD calculations of O+Au ($2.0 < y < 3.0$) are included.

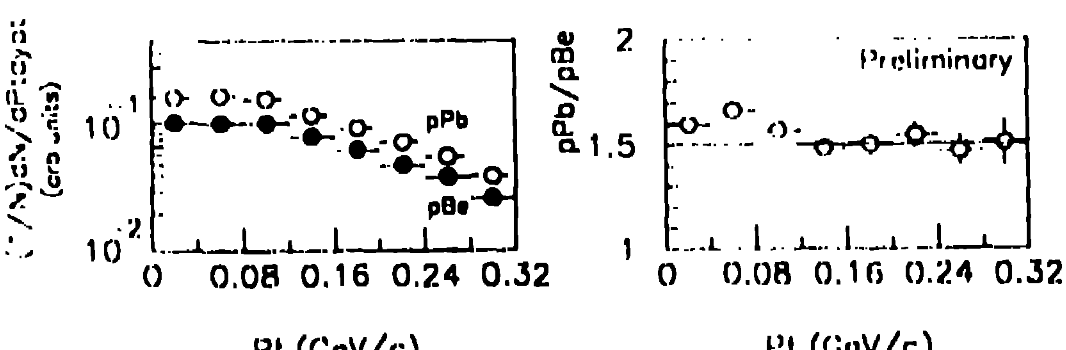

Figure 3. NA44 pion p_T distributions from pA collisions. These data have been corrected for variations in dN/dy within the NA44 acceptance.

are contained in the low temperature exponential [7].

E802/E859/E866 has studied low p_T pions in the rapidity range 1.2-1.4. Preliminary studies from E802 indicate that there may be a slight low p_T enhancement in new data sets which measure to $p_T \approx 200$MeV/c in Si+A reactions [29, 30]. E866 is the third generation E802 experiment and stuc'.es Au+Au reactions at 11.6GeV/c. They report an enhancement at low m_T which seems to show a difference between the π^+ and the π^- spectra; only the π^- distributions show an enhancement. There is no strong dependence on y. It has been estimated that approximately 25% of the negative pions are contained in the low temperature exponential [9].

Experiment E814 measures identified pions at 14.6GeV/c in the rapidity range 2.8-3.6. An enhancement is seen in the data when compared to Boltzmann and m_T exponential fits. The data show no strong dependence on target or rapidity [8, 32]. They also report no enhancement in pA results [31] and no difference between their π^+ and π^- distributions [32].

In comparing the CERN and AGS results, several interesting experimental trends can be extracted. Both the CERN and AGS hadron spectra show a low p_T enhancement when compared to pp minimum bias results, m_T exponentials, or a thermal fit. pA collisions studied at CERN show an enhancement similar in magnitude to the AA results. There is a weak dependence on target and projectile. B. Jacak has fit the CERN results with a sum of two exponentials in m_T to estimate the fraction of soft pions contained in the low p_T region [20]. Although the choice of a fitting procedure can influence the absolute results, this exercise shows a general trend; the magnitude of the enhancement of soft p_T hadrons at CERN energies compared to minimum bias pp results is strongest at backwards rapidities. E866 sees a rise in their negative but not positive pion spectra. E814 and NA44 see no difference between π^+ and π^- results. NA34 and NA44 report no strong dependence on centrality. While there is no strong dependence on rapidity at AGS energies, the CERN data show an obvious dependence, with the low p_T enhancement more significant at backwards rapidities [12, 20].

3. THEORETICAL POSSIBILITIES

Several intriguing explanations have been proposed to explain the low p_T behavior. Lee, Heinz [18], and Atwater [2] have suggested that this could be due to collective effects; transverse flow could lead to a concave shaped cross section. Lee and Heinz compared NA35 S+S data (mid-rapidity) to a global fit of a thermal model that included radial collective flow. They found good agreement except at very low p_T. However, this theory does not explain why the enhancement at CERN in pA $\approx$ AA or why the CERN data show a rapidity dependence.

Van Hove suggested we could be observing the decay of small plasma droplets into pions [17]. As intriguing as this sounds, this is an effect that would be peaked at mid rapidity, contrary to the CERN results.

Several theorists have suggested that the system could be out of chemical equilibrium. Kataja and Ruuskanen state that the experimental p_T spectra can be described by a thermal distribution if one assumes that there is a strong excess of pions with respect to chemical equilibrium at freezeout; a positive chemical potential would lead to the production of more pions [14]. Gavin and Ruuskanen further claim that the system may only be in partial thermal equilibrium due to a longitudinal expansion leading to additional soft pions [15]. Barz et al., have calculated a monte carlo solution of a Boltzmann equation for a meson gas including resonances and incomplete thermalization; they find good agreement with NA35 mid-rapidity O+Au results [16]. These theories ignore the influence of the baryons in the system and do not attempt to explain low p_T behavior other than at mid-rapidity. Nor do they predict a similar enhancement in pA and AA collisions.

Shuryak proposed that we could be observing a modification of the pion dispersion relation [13]. Attractive interactions between constituents could form a surface making it difficult for constituents to leave the system, trapping the low p_T pions in a potential well. A search for this effect at LAMPF indicated its absence, at least in the relatively cold nuclear matter present in pA collisions [33]. It is certain that this mean field effect as proposed by Shuryak must exist at some level; the question is whether it is large enough to explain the observed features in the data. Koch and Bertsch have found collective mean fields insufficient to explain the magnitude of the observed enhancement unless there is an extremely slow adiabatic expansion which they find unrealistic [36].

Sullivan and Simon-Gillo have studied secondary pion production in the target. Geant was used to track particles generated from RQMD calculations (200GeV/A S+Pb and 14.6GeV/A Si+Pb) and the secondaries created in the target through various target thicknesses[34, 35]. The calculation indicated that thick targets could lead to a significant low p_T enhancement peaked at backwards rapidities both at CERN and the AGS (figure 4). However, the experiments either used thin targets or studied a rapidity region where a thick target had negligible effect.

Many theorists and experimentalists (Heinz, Brown, Cole, Jacak, Koch, Sollfrank, Stachel, and Welke) have recognized the influence of resonances on the p_T distribution of hadrons [19, 21, 10, 20]. RQMD calculations and experimental results indicate that mesonic resonances dominate at mid-rapidity at CERN, while AGS collisions produce a more baryonic environment.

4. COMPARISON OF DATA TO MODELS

Figure 5a (top) shows RQMD calculations at CERN and AGS energies to illustrate the contribution of pions from various resonances. π arising from primary collisions, strings and ropes are summed together; RQMD ropes are interactions between strings [35]. In this calculation, the resonances are grouped as follows: baryonic: Δ, N^*, Δ^*; strange: K^0_s, Λ, Σ; mesonic: η, η', ω; pions from ρ's are kept separately. Most of the pions at mid-rapidity at CERN energies are from ρ's and primary collisions, while the baryonic resonances play a more important role near target rapidity. The mesonic and strange resonances play a comparable role and peak at mid-rapidity. At AGS energies, the baryonic resonances dominate at all rapidities. Figure 5b (bottom) shows rapidity density plots for pions with $p_T < 300$ MeV/c from RQMD. At CERN energies, baryonic resonances dominate at target rapidity. The other contributions become comparable and peak at mid rapidity. This plot explains how a rapidity dependence of the low p_T enhancement at CERN could exist. The shape of the rapidity density at the AGS does

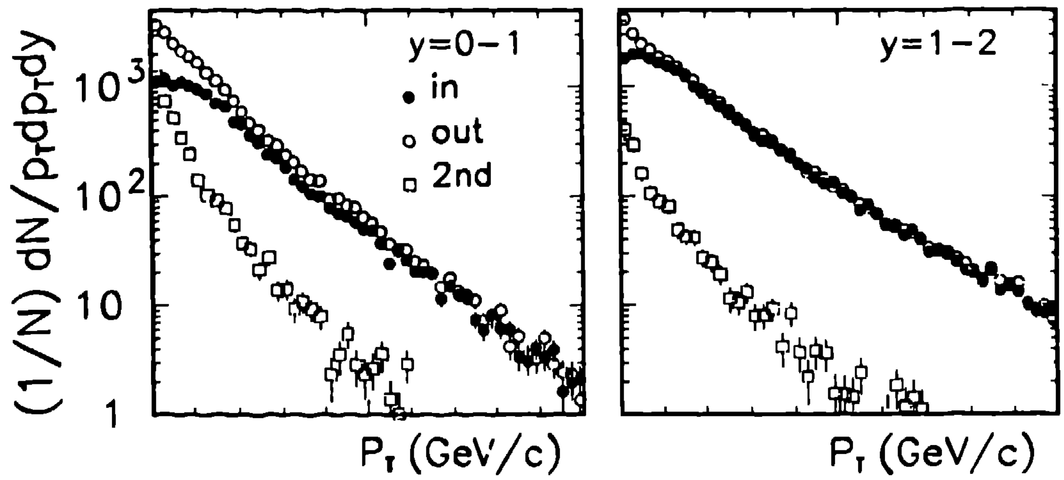

Figure 4. RQMD/GEANT calculation showing the affect of secondary pions created in the target on the p_T distribution of pions at target rapidity at CERN energies. "in" are the particles generated by RQMD for 200GeV/A S+Pb. Particles and the secondaries created in a 10mm Pb target are tracked with Geant. "out" are al' resulting negative pions 'racked by GEANT found in a given y range. "2nd" are secondary pions only in the same y range.

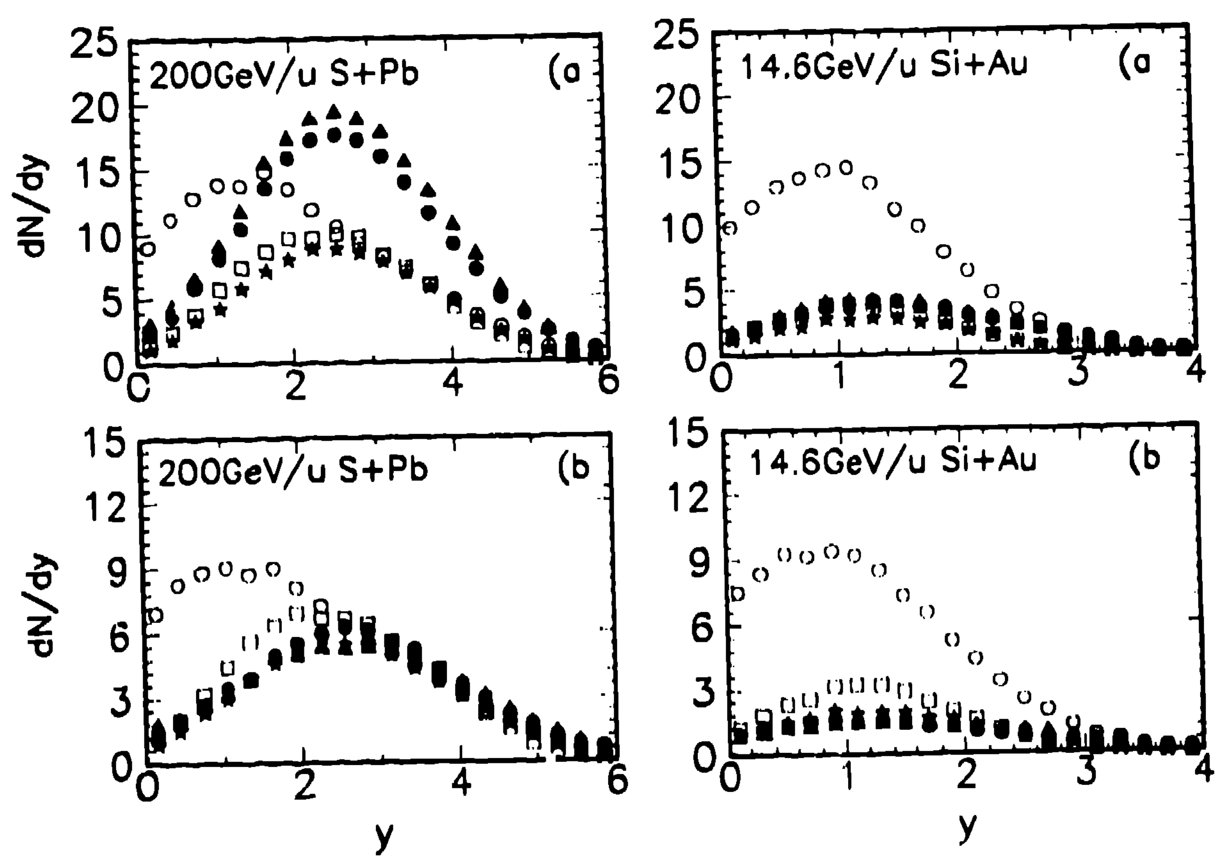

Figure 5. a) (top) RQMD rapidity density plot of pions from various sources at both CERN and AGS energies: ● from collisions, strings and ropes, ○ baryonic, □ mesonic, ★ strange, ▲ ρ 's. b) (bottom) same plot for low p_T pions (<300MeV/c)

not change significantly for low p_T pions alone; the baryonic resonances still dominate at all rapidities. Consequently, one might expect a weak dependence of low p_T enhancement on rapidity at AGS energies.

Several experimental groups have compared to models that incorporate resonance contributions. E810 and E814 pion p_T spectra are well described by RQMD and/or ARC results [8, 37]. E814 also compared reconstructed Δ's to RQMD predictions and found good agreement [8]. NA44 S+Pb pion spectra ($3.1 < y < 4.1$) are also well described by RQMD. The comparison of an RQMD O+Au calculation to NA34 is shown in figure 1 and the comparison to NA35 is in figure 2. (The K_s and Λ are included in both of these data sets and therefore allowed to decay in RQMD.) The RQMD results are scaled in order to compare to the data which are presented here in arbitrary units. It is interesting, however, that RQMD does not reproduce the magnitude of the low p_T enhancement at backwards rapidities.

5. CONCLUSION

Low p_T enhancement has been observed in AGS and CERN heavy ion results. At CERN a similar behavior is observed in pA and AA collisions. The CERN results show a strong rapidity dependence which is reflected in the rapidity distribution of pions from resonances. The AGS results are well described by models incorporating resonances; these data, as well as the distributions of the pions from the contributing resonances, do not show a strong rapidity dependence. RQMD results do not fully reproduce the magnitude of the enhancement backwards of mid-rapidity at CERN, leaving room for further speculation. In order to understand the CERN results, theoretical models should incorporate the influence of resonances, address the fact that the pA ≈ AA results, and explain the rapidity dependence observed in the data.

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