Measurement of the average transverse momentum and of the pion-emission volume in proton-nucleus and antiproton-nucleus reactions at 200 GeV

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We have measured $\langle p_\perp \rangle$ as a function of multiplicity for the reaction proton (antiproton) on proton, neon, argon, and xenon. For all reactions, $\langle p_\perp \rangle$ is independent of multiplicity. We observed that the pion-emission volume is the same for both hydrogen and xenon targets and has a radius about 1.5 fm. Our analysis shows no indication of a deconfinement phase transition in nuclear matter.

I. INTRODUCTION

This paper reports on measurements which give some information on the temperature and the size of the hadronic interaction volumes. We have concentrated our investigation on a comparison of hadronic interactions on protons and nuclear targets.

In the last few years properties of superdense matter have been discussed widely and the description of a quark-gluon plasma in thermodynamical language has regained popularity.[1] In the thermodynamical model[2] the multiplicity is proportional to entropy and the average transverse momentum $\langle p_\perp \rangle$ is related to the temperature and the size of the interaction volume. More quantitative treatments of the thermodynamical model, using lattice gauge calculations in QCD,[3] predict a quark-gluon deconfinement phase transition at the surprisingly low temperature of about 200 MeV.

In this experiment we observe in the central rapidity region twice as many particles per rapidity unit with the xenon target as with the proton target (see Table II). This means[4] that for central collisions the average energy density is much higher than inside the stationary nucleon where the density is about 440 MeV/fm^3. Many authors have speculated that at higher energy densities a quark-gluon plasma could be produced, which may extend over several fermis.[1]

The paper is organized as follows: The data analysis pertinent to this investigation is described in Sec. II. In Sec. III we present $\langle p_\perp \rangle$ as a function of multiplicity and compare our results with recent measurements from the proton-antiproton collider at CERN. In Sec. IV we compare Bose-Einstein correlations of like- with unlike-charged-particle pairs in order to obtain the size of the interaction volume. The conclusions are contained in Sec. V.

II. DATA ANALYSIS

This experiment was performed at the CERN SPS, using a streamer-chamber vertex spectrometer with a 4π-solid-angle coverage and excellent multitrack efficiency. The magnetic field of 1.5 T provided good momentum and charge information. Range, ionization, and decay signature were used to identify particles having momentum below 600 MeV/c. The particles with momentum above 600 MeV/c were treated as pions. A downstream spectrometer consisting of seven magnetostrictive spark chambers was used to improve the momentum measurement. The measuring accuracy was $\Delta p/p = 0.0025p$ (p in GeV/c) in the streamer chamber and $\Delta p/p = 0.0005p$ for tracks also reconstructed in the spark chambers. This accuracy was important in order to obtain sufficient resolution to measure the dimensions of the interaction volume up to several fermis in size. Only 10% of the charged tracks with momentum $p > 30$ GeV/c had to be reconstructed using streamer-chamber data only. Our interaction trigger vetoed about 3% of the inelastic events. Ad-

TABLE I. Numbers of events and pairs for proton and xenon targets.

Reaction	No. of events	No. of like pairs	No. of unlike pairs	No. of like pairs after cuts[a]	No. of reshuffled unlike pairs after cuts[a]
$p+p$	3531	55 481	63 494	7 203	6 891
$\bar{p}+p$	1850	26 440	33 052	3 465	3 559
$p+$Xe	1391	146 220	138 773	13 971	11 219
$\bar{p}+$Xe	1381	155 627	157 722	15 540	12 756

[a] $q_0 < 0.2$ GeV, $0.002 < q_t^2 < 0.2$ (GeV/c)^2.

ditional details of this experiment have already been published elsewhere.[5] Tables I and II show the number of events, tracks, and pion pairs for each reaction used in this analysis.

III. INVESTIGATION OF TRANSVERSE-MOMENTUM DISTRIBUTIONS

Figure 1 shows the $\langle p_\perp \rangle$ of charged particles as a function of charged multiplicity for the central rapidity region $|y| < 1.5$ for several targets. The rapidity

$$y = \frac{1}{2}\ln\frac{E+p_{\parallel}}{E-p_{\parallel}}$$

is calculated in the overall pp center-of-mass system (c.m.s.). The dashed lines represent $\langle p_\perp \rangle$ for all multiplicities, the values of which are given in Table II along with the average multiplicity $\langle n \rangle$. We see no correlation of $\langle p_\perp \rangle$ with the multiplicity, in agreement with the results at the lowest energy of the CERN ISR.[6] At higher energy an increase of $\langle p_\perp \rangle$ with multiplicity was indicated by cosmic-ray measurements of Lattes *et al.*[7] A clear correlation was observed in a $p\bar{p}$ collider experiment at CERN,[8] the results of which are represented by the pair of solid lines (± 1 standard deviation) in the $\bar{p}Xe$ diagram of Fig. 1. This observation was interpreted, within the framework of Landau's thermodynamical model,[2] by Van Hove[9] as possible evidence for a hadronic phase transition.

IV. DETERMINATION OF THE INTERACTION VOLUME FROM PION CORRELATIONS

The like-pion interference, first observed by Goldhaber *et al.*,[10] allows one to determine the time-space characteristics of the pion-emission volume.[10] The two-particle correlation function of identical bosons emitted with nearly equal momentum p, and opening angle θ by two independent one-particle sources, is described by the formula

$$W = 2[1+\cos(pR\theta)] ,$$

where R is the distance between the two sources.

However, this formula holds only for two point sources. To analyze our data we used the specific parametrization for a model of a uniformly radiating disc of radius R and lifetime τ, which was developed by Kopylov and Podgoretsky.[11] In addition to the energy and momentum differences of two pions, calculated in the overall pp c.m.s. by

$$q_0 = |E_i - E_j| \text{ and } \vec{q} = \vec{p}_i - \vec{p}_j ,$$

they introduced a new variable

$$q_t = \frac{|(\vec{p}_i - \vec{p}_j)\times(\vec{p}_i + \vec{p}_j)|}{|\vec{p}_i + \vec{p}_j|} ,$$

where q_t is the projection of $\vec{q}$ onto the plane perpendicular to $\vec{p}_i + \vec{p}_j$. It is closely related to the effective mass $M_{\pi\pi}$ (for $q_0 \to 0$, $q_t^2 = M_{\pi\pi}^2 - 4m_\pi^2$).

In this model, the ratio of like-sign pairs (N_L) to background pairs (N_B) in small intervals of q_0, q_t is given by the expression

$$\frac{N_L}{N_B} = 1 + \frac{I^2(q_t R)}{1+(q_0\tau)^2} ,$$

where

TABLE II. Number of events and average transverse momentum $\langle p_\perp \rangle$ and multiplicity $\langle n \rangle$ of charged particles in the rapidity region $|y_{\text{c.m.s.}}| < 1.5$.

Reaction	No. of events	No. of tracks	$\langle p_\perp \rangle$ (GeV/c)	$\langle n \rangle$
$p+p$	3252	17 778	0.366±0.002	5.47±0.06
$\bar{p}+p$	1643	8 724	0.366±0.003	5.31±0.08
$p+$Ne	104	658	0.376±0.010	6.33±0.39
$\bar{p}+$Ne	82	505	0.372±0.012	6.16±0.40
$p+$Ar	929	7 857	0.376±0.003	8.46±0.18
$\bar{p}+$Ar	835	7 257	0.376±0.003	8.69±0.20
$p+$Xe	1344	14 070	0.363±0.003	10.50±0.18
$\bar{p}+$Xe	1341	14 628	0.359±0.003	10.95±0.18

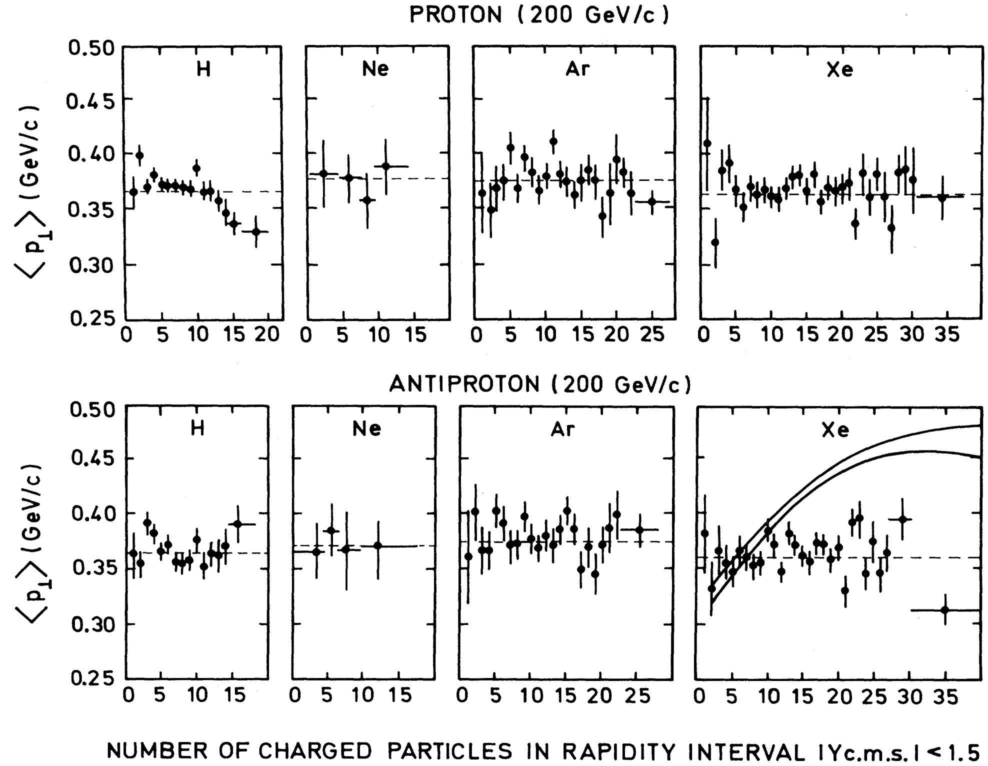

FIG. 1. The average transverse momentum of charged hadrons ($\sqrt{s}=19.4$ GeV) as a function of charged track multiplicity in the rapidity interval $|y|<1.5$. The dashed line is the $\langle p_\perp \rangle$ value. The solid lines represent (± 1 standard deviation) the result of Ref. 8.

$$I(q_t R)=\frac{2J_1(q_t R)}{q_t R},$$

with J_1 being the first-order Bessel function. N_B is the number of "background" pairs, i.e., the number of pairs if there were no correlations.

In order to extract only the correlation arising from Bose-Einstein statistics, but not other possible dynamical and kinematical correlations, one takes a restricted q_0, q_t kinematical region. For N_B one usually takes the number of opposite-sign pairs. Unfortunately the dependence of this N_B on q_0, q_t is not free of dynamical correlations. In fact the $(\pi^+\pi^-)$ mass spectrum and hence the q_t distribution is strongly affected by resonances such as η and ω. A discussion of possible ways to determine N_L and N_B is given in Ref. 12.

We now summarize the procedure chosen for this analysis. In order to suppress the contribution of resonances we used only pairs with $q_0<0.2$ GeV and $0.002<q_t^2<0.2$ (GeV/c)^2; the lower limit removes possible electron-pair contamination. N_B was found by first randomly mixing the transverse momentum components of pions in each event. Then the variables q_t and q_0 of the randomly mixed pairs were computed in the c.m.s. of the interaction in the same manner as for the nonreshuffled events. Finally N_B was normalized to the total number of like pairs in the q_0, q_t^2 region given above.

The experimental ratio N_L/N_B in bins of q_0 and q_t^2 was fitted with the least-squares method to the modified Kopylov-Podgoretsky expression

$$\frac{N_L}{N_B}=C\left[1+\lambda\frac{I^2(q_t R)}{1+(q_0\tau)^2}\right], \tag{1}$$

where C is a normalization constant and λ the degree of incoherence ($\lambda=1$ represents a fully incoherent source). The maximum value of the function (1) is given by $C(1+\lambda)$. Introducing λ we take into account effects not originating from Bose-Einstein correlations.

In Fig. 2, we show the ratio N_L/N_B, i.e., the experimental correlation function versus q_t^2 for two intervals of q_0, for both incident particles and for hydrogen and xenon targets. The solid line represents the fit of the theoretical expression [Eq. (1)] to the data. This fit was made simultaneously for both q_0 intervals. In Table III the fitted parameters with the corresponding χ^2 are given. The fitted values for λ and C are close to one and the radius R is about 1.5 fm for all four reactions. The fitted value of C close to one indicates that our N_B normalization is reasonable. The result for $\bar{p}p$ is in good agreement with a previous experiment.[12]

As a check the fit was tried for different q_t^2 (0.015 GeV^2/c^2) and q_0 (0.05 GeV) bins. The fit results were almost the same. We also tried the fit with λ as a fixed pa-

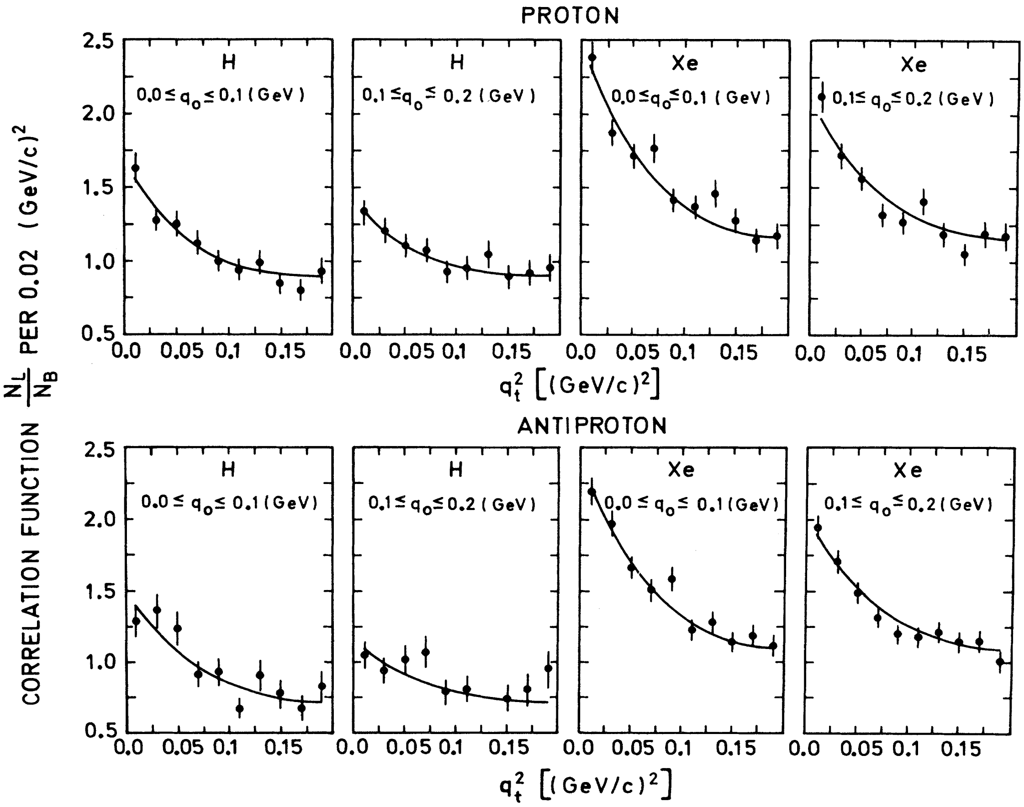

FIG. 2. q_t^2 dependence of the correlation function for the two intervals of q_0. The curves are fits of Eq. (1) to the data.

rameter: $\lambda=1$ and $\lambda=0.5$. For the case $\lambda=1$, we found results similar to the case where λ was a free parameter. In the case $\lambda=0.5$, the value of R did not change, but τ was very small ($c\tau\approx0.01$ fm for pXe).

Since our interaction volume is probably not a simple sphere, but more likely an ellipsoid, we tried to make specific cuts, in order to measure its length and width. We define ϑ to be the angle between the beam axis and the momentum vector of the pion pair and ϕ to be the angle between the plane defined by the two pions and the plane

TABLE III. Fitted values of model parameters [see Eq. (1) in text].

Reaction	Cuts	R (fm)	$c\tau$ (fm)	λ	C	χ^2 (NDF=16)
pp	Average	1.66±0.04	1.02±0.18	0.96±0.08	0.90±0.02	9.0
	Length	1.02±0.08	0.62±0.25	1.14±0.10	0.65±0.02	8.4
	Width	1.74±0.11	1.04±0.28	1.04±0.15	0.90±0.03	13.5
$\bar{p}p$	Average	1.51±0.08	1.31±0.21	1.30±0.20	0.72±0.02	29.8
pXe	Average	1.53±0.13	0.93±0.16	1.27±0.11	1.14+0.05	25.4
	Length	0.82±0.05	0.94±0.16	1.52±0.11	0.78±0.03	15.1
	Width	1.58±0.12	0.89±0.17	1.38±0.13	1.14±0.05	23.2
pXe	$n>20$	1.45±0.11	0.95±0.10	1.55±0.16	1.12±0.05	21.1
$\bar{p}$Xe	Average	1.47±0.11	0.95±0.11	1.34±0.08	1.07±0.05	14.7
	Length	1.36±0.10	0.78±0.28	0.94±0.11	1.18±0.04	10.9
	Width	1.48±0.11	0.98±0.12	1.43±0.11	1.04±0.06	11.8
$\bar{p}$Xe	$n>20$	1.53±0.10	0.95±0.16	1.27±0.12	1.16±0.05	19.1

defined by the beam axis and the momentum vector of the pion pair. In the part of the data where $|\cos\vartheta|$ is small and $|\cos\phi|$ is approximately one, the fitted values of R will be dominated by the length of the interaction volume. To obtain adequate statistics, we used cuts of $|\cos\vartheta| < 0.5$ and $|\cos\phi| > 0.7$. In the complementary data sample the value of R will be dominated by the width of the interaction volume. The results of these fits are also shown in Table III (except for $\bar{p}p$ where statistics were inadequate) and they indicate that the width of the interaction volume is larger than the length.

The values of the fitted parameters are similar for hydrogen and xenon, which we would not expect if a quark-gluon plasma were produced in the nuclear target. This result rather agrees with the expectation from the additive quark model, which was found to be consistent with many other aspects of hadron-nucleus collisions.[5]

Central collisions are expected to be more favorable for the production of a quark-gluon plasma, because they produce a higher energy density. We have attempted to enrich the event sample with central-collision events by selecting xenon events with overall charged-pion multiplicity greater than 20. However, even with this multiplicity requirement we still obtained similar R and $c\tau$ values (see Table III).

It is interesting to compare the radius of interaction found in this analysis using elementary projectiles with that found in the Bevelac experiments using the projectile ^{40}Ar.[13] Their radius is about three times ours, consistent with the larger radius of ^{40}Ar. However, in contrast with our results, their R increases with multiplicity. Similar results are obtained at the CERN ISR.[14] The size of the formation zone of pions was also measured in e^+e^- annihilation.[15] It was found to be a factor of 2 smaller than in hadron-hadron and hadron-nucleus collisions.

V. CONCLUSIONS

We have investigated the correlation between $\langle p_\perp \rangle$ and multiplicity in the central rapidity region. No correlation is observed in contrast to experiments at higher energies.

We have obtained values for the size and lifetime of the pion-emission volume in both hadron-proton and hadron-xenon interactions. The radius is about 1.5 fm in both cases. This result is consistent with our previous observation that the proton interacts inside the nucleus in the manner predicted by the additive quark model.[5]

This analysis shows no indication of a deconfinement phase transition in nuclear matter.

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[1]E. V. Shuryak, Phys. Rep. 61, 71 (1980).

[2]L. D. Landau, *Collected Papers of L. D. Landau,* edited by D. ter Haar (Pergamon, London, 1965), p. 569.

[3]See, e.g., L. McLerran *et al.*, Phys. Lett. 98B, 195 (1981); J. Engels *et al.*, *ibid.* 101, 89 (1981); see Ref. 1.

[4]J. D. Bjorken, Phys. Rev. D 27, 140 (1983).

[5]C. de Marzo *et al.*, Phys. Rev. D 26, 1019 (1982).

[6]T. Åkesson *et al.*, Phys. Lett. 119B, 464 (1982); M. Faessler, Report No. CERN-EP/82-145, 1982 (unpublished).

[7]C. M. G. Lattes *et al.*, Phys. Rep. 65, 151 (1980).

[8]G. Arnison *et al.*, Phys. Lett. 118B, 167 (1982).

[9]L. van Hove, Phys. Lett. 118B, 138 (1982).

[10]R. Hanbury Brown and R. Q. Twiss, Nature (London) 178, 1046 (1956); G. Goldhaber *et al.*, Phys. Rev. 120, 300 (1960); G. Cocconi, Phys. Lett. 49B, 459 (1974); M. Gyullassy *et al.*, Phys. Rev. C 20, 2267 (1979).

[11]G. I. Kopylov, Phys. Lett. 50B, 472 (1974); G. I. Kopylov and M. I. Podgoretsky, Yad. Fiz. 19, 434 (1974) [Sov. J. Nucl. Phys. 19, 215 (1974)].

[12]M. Deutschmann *et al.*, Nucl. Phys. B204, 333 (1982).

[13]S. Y. Fung *et al.*, Phys. Rev. Lett. 41, 1592 (1978); J. J. Lu *et al.*, *ibid.* 46, 898 (1981).

[14]T. Åkesson *et al.*, Report No. CERN-EP/83-74, 1983 (unpublished).

[15]G. Goldhaber, in *Proceedings of the International Conference on High Energy Physics, Lisbon, 1981,* edited by J. Dias de Deus and J. Stoffer (European Physical Society, Erice, 1982), p. 767; W. Koch, in *Proceedings of the* XIIIth *International Symposium, Multiparticle Dynamics, Voldendam, The Netherlands, 1982,* edited by E. W. Kittel, W. Metzger, and A. Stergiou (World Scientific, Singapore, 1983), p. 543.