BNL--36789

DE85 017522

BNL 36789

CONF-8505166-3

RELATIVISTIC HEAVY ION PHYSICS

Ole HANSEN

Brookhaven National Laboratory, Physics Department*, Upton, NY 11973 USA

1. INTRODUCTION

In the fall of 1986 beams of heavy ions up to $A=40$ at total energies up to $E=225$ GeV/nucleon will become available for experiments at CERN (60 and 225 GeV/nucleon) and at Brookhaven (15.5 GeV/nucleon). Are these energies interesting in relation to the ideas of creating quark deconfinement?

The energy density of nuclear groundstates¹ is

$$\epsilon_0 = \frac{A}{\frac{4\pi}{3} R^3} = 0.17 \text{ GeV}/(\text{fm}^3 \text{c}^2) \quad (1)$$

i.e., about 3 times smaller than the nucleon density

$$\epsilon_0^B = \left(\frac{4\pi}{3} 0.8^3\right)^{-1} = 0.43 \text{ GeV}/(\text{fm}^3 \text{c}^2) \quad (2)$$

In order to make the quark wavefunctions from different nucleons overlap, a nuclear energy density exceeding that of Eq. (2) certainly must be obtained. The "bag" radius in Eq. (2) is taken as 0.8 fm, but a number as 0.6 is just as reasonable. Thus densities of

$$\epsilon/\epsilon_0 \geq 3 \text{ to } 7 \quad (3)$$

should be the goal.

The energy deposition in relativistic heavy ion collisions is not known. Interpreting the proton plus nucleus data of Ref. 2, Busza and Goldhaber deduced³ that in a central collision with a Pb-nucleus the average slowdown is

$$\Delta y = -2.5 \pm 1.0 \quad (4)$$

where the rapidity y is defined as

$$y = \frac{1}{2} \ln \frac{E+P_{\parallel}}{E-P_{\parallel}} = \tanh^{-1}(P_{\parallel}/E) . \quad (5)$$

Here E is the total energy and $P_{\parallel}$ is the momentum component along the beam axis. For the beam itself, $P_{\parallel}=P$, so

$$y_{\text{beam}} = \tanh^{-1}(\beta) \quad (6)$$

where β is the velocity in units of the speed of light in vacuum. The semi-empirical rule (4) has been substantiated recently from theoretical calculations by Date, et. al.⁴

*Work performed under Contract #DE-AC02-76CH00016 with the U.S. Department of Energy.

For symmetric (A+A) collisions the rapidity in the center of mass frame is

$$y_{c.m.} = y_{lab} - y_G = \frac{1}{2}y_{lab} \quad (7)$$

where y_G is the lab rapidity of the center of mass. For the three beam energies 225, 60, and 15.5 GeV/nucleon the c.m. rapidities in A+A collisions are 3.09, 2.42, and 1.75, respectively. Thus if the rule (4) is applicable at these energies (it was derived from 100 GeV proton data) the two lowest energies would correspond to complete stopping of the nuclei in the c.m. system while some "transparency" would occur at the higher energy. With the uncertainties in Eq. (4), full stopping may occur at all energies, and almost certainly at 15.5 GeV/nucleon.

Calling the total energy in the c.m. system $\sqrt{s}$, the energy density at full stopping ($\beta_{c.m.}=0$) is

$$\epsilon/\epsilon_0 = (\sqrt{s}/(\frac{4\pi}{3}r_0^3 A))/(\frac{Am_N}{(\frac{4\pi}{3}r_0^3 A)}) = \frac{\sqrt{s}}{Am_N} \quad (8)$$

where A is the number of nucleons and m_N is the rest energy of a nucleon, 0.935 GeV. Using standard kinematics formulae, we can rewrite Eq. (8) as

$$\epsilon/\epsilon_0 = [2 + \frac{2E}{Am_N}]^{1/2} \quad (8a)$$

where E/A is the lab energy per nucleon. For the Brookhaven beam $(\epsilon/\epsilon_0)_{AGS} = 5.9$ and for the 60 GeV beam at CERN, $(\epsilon/\epsilon_0)_{SPS} = 11$. Although these estimates are crude, they indicate that the energy ranges of the new program certainly are of interest to the quark deconfinement problem.

2. THE PLANNED EXPERIMENTAL PROGRAM

There are four large experiments planned at CERN; NA34, an experiment aiming at detection of leptons with extensive calorimetry and a small solid angle magnetic spectrometer⁵; NA35, centered around a streamer chamber and also featuring calorimetry; NA36, built for detection of strange particles (e.g. Λ 's, cascades and Ω^-), using a sweeping magnet and a time projection chamber and, finally, the plastic ball and calorimetry experiment in the west area (for the three latter see, e.g., Ref. 6). At Brookhaven two large experiments have been approved; E-810 which* will use an existing magnetic spectrometer equipped with a new time projection chamber, and E-802, to be discussed in some detail below. The CERN experiments were discussed in some detail at the VISBY conference^{5,6} where the Brookhaven heavy ion collider project ($\sqrt{s}/A = 200$ GeV/nucleon) was also discussed.⁷

*Copies of the proposal for AGS experiment E-810 may be obtained from the spokesmen, E. Plattner and S. Lindenbaum at Brookhaven National Laboratory.

interaction trigger ($Z_{\text{final}} < Z_{\text{beam}}$) or a central trigger ($Z_{\text{final}} = 0$). The target is surrounded by proportional counter tubes, segmented into 4000 independent readouts. This hodoscope counts number of charged particles and gives the direction of each by invoking the target position. An opening in the system provides unobscured access to the spectrometer. On the righthand side an electromagnetic calorimeter, consisting of 300 lead-glass blocks and corresponding front counters, is placed near 20° lab angle, i.e. near 90° in the nucleon-nucleon center of mass system ("midrapidity" in the high energy language).

The kinematic coverage for kaons (similar for π and p) of the spectrometer is shown in Figure 2, where particle rapidity (Eq. 5) is plotted versus particle transverse momentum. The quark deconfinement is expected to take place at

FIGURE 2
Kinematic acceptance of spectrometer

temperatures larger than the pion mass of 140 MeV, i.e. temperatures where the protons and neutrons may create pions quite freely in their thermal collisions, leading to energy densities fulfilling the condition (Eq. 3). The radiation from a source at, say, 200 MeV has typical momenta of that size. If we want to follow spectra over, e.g., 3 orders of magnitude, we should span a range of transverse momenta of ≈ 1.5 GeV/c. At 90° in the c.m. system, $y = y_0/2$ in Figure 2, where y_0 is the beam rapidity of 3.50, we should cover up to $p_T \approx 2$ GeV/c, i.e. up to $p = 5$ GeV/c in the lab system (full curves in the figure with the numbers 1, 2, 3, 5, etc. being in GeV/c). The corresponding lab angle (broken curves) is 20° . Such arguments decided the necessary acceptance of the spectrometer and thus set the geometry.

The experiment can then measure spectra as function of multiplicity and transverse neutral energy flow, providing information on effective temperatures and production cross sections. Data on deuterons and A=3 or 4 products can provide measures of the entropy increase. The solid angle of the spectrometer will allow studies of two particle correlations of p, π , and K leading to estimates of source sizes. K^+ - K^- correlations will be measured and analyzed to yield production rates for ϕ -mesons (strange and anti-strange quark pair). Cross sections for anti-particle production (p,d,-) will be investigated. Thus E-802, besides providing basic information on nucleus-nucleus collisions at 15.5 GeV/nucleon (hereunder stopping), will be sensitive to some of the crucial variables for detecting a quark deconfinement phase transition, such as temperature, entropy, "enhancements" of strange particles and antibaryons.

As a final example of the demands on detectors in high energy heavy ion reactions, let me discuss the problem of segmentation briefly. Figure 3 shows the first tracking chamber, 20 cm x 10 cm. The symbols indicate hits, produced

FIGURE 3
Front tracking chamber with generated hits

by a Monte-Carlo event generator (HIJET⁹). Only charged particles register in a tracking device, so the relevant multiplicity in this event is 12. If n particles hit uniformly on a counter of s identical segments, the probability of registering k hits is

$$P(k) = \binom{s}{k} k! \left(\frac{1}{s}\right)^n \frac{s^{(k)}}{s_s} \quad (9)$$

2.1. E-802, An example of a high-energy heavy ion experiment

Experiment E-802 follows the concepts of the BEVALAC work of S. Nagamiya et al. (see, e.g. Ref. 8). An outline of the experimental setup is shown in Figure 1. The main feature is a single arm magnetic spectrometer with two tracking counters before the magnet and two after, for momentum determination

FIGURE 1
Layout of E-802

($\Delta p/p \approx 0.5\%$). Particle identification is accomplished by time-of-flight measurements to a wall of scintillators placed all the way toward the end of the spectrometer platform (distance $\approx 7.5\text{m}$, $\Delta t \approx 100\text{ ps}$), combined with two Cerenkov counters (indicated in the figure as one blank box between the two rear tracking counters). The first counter will use aerogel as a light source with a pion threshold at $\approx 0.8\text{ GeV/c}$ and segmentation of ≈ 100 . The second counter will use freon gas at pressures up to 4 atmospheres, with a pion threshold down to $\approx 2.0\text{ GeV/c}$. (In the present configuration both rear tracking counters come before the Cerenkov counters.) This arrangement will identify $p^\pm$, $\pi^\pm$, and $K^\pm$ up to momenta of $\approx 4\text{ GeV/c}$ with anticipated K-abundancies ≈ 20 times smaller than the π -abundancies. The solid angle is about 25 msr.

The Cerenkov complex consists of a combination of tracking chambers, high pressure Cerenkov vessels and time-of-flight scintillators and will provide particle identification up toward 20 GeV/c in small solid angle of $\approx 1\text{ msr}$.

The counters around the beam provide trigger and subsidiary information. Upstream (not shown) there is a beam counter defining the Z^2 and the geometry of the beam. The forward counter measures Z^2 after the target and thus provides an

where the last symbol is Sterling's number of the second kind, well known to practitioners of the art of measuring gamma-ray multiplicities. We chose as a performance criterion that

$$P(n) + P(n-1) = \left(\frac{S}{n}\right)n! \left(\frac{1}{S}\right)^n + (n-1)! \left(\frac{1}{S}\right)^{n-1} \left(\frac{n}{2}\right) = 0.95 \quad (10)$$

i.e. we will allow no more than one segment of the detector to have a double hit in the vast majority of cases. The criterion Eq. (10) leads to a simple scaling law

$$\frac{S}{n^2} = \text{constant} \quad (11)$$

For $n=15$, the segmentation of the tracking chambers and the time-of-flight wall must be ≈ 225 to satisfy Eq. (10).

The criterion (10) puts severe constraints on the allowed multi-hit probability for a single segment, i.e.

$$P(i, \text{multiple hit}) = 1 - \left(1 - \frac{1}{S}\right)^{n-1} \left(1 + \frac{n-1}{S}\right) \quad (12)$$

which, by the way, does not follow the scaling law of Eq. (11). In our example, $s=225$, $n=15$, $P(i, \text{multi-hit}) \leq 2 \times 10^{-3}$. The criterion chosen reflects that it is the total number of complicated hits on a detector that determines our ability to disentangle the event.

ACKNOWLEDGEMENT

Experiment E-802 is a collaboration between Brookhaven, Hiroshima, LBL, MIT, Tokyo, and Waseda, with spokesmen S. Nagamiya and O. Hansen. I am indebted to all my collaborators for help in this presentation. I am particularly indebted to C. Chasman and P.D. Bond for allowing me to present the hit discussion which was worked out in collaboration with them.

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