Relativistic Heavy-Ion Collisions*†

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It gives me great pleasure to be here in Taipei to participate in the First International Symposium on Symmetries in Sub-Atomic Physics.

One of the great masters in probing symmetry properties in sub-atomic physics is Ernest Henley, as is borne out by the following examples of his publications.

VOLUME 16, NUMBER 16 PHYSICAL REVIEW LETTERS 18 APRIL 1966

PRECISION TESTS OF T INVARIANCE IN ELECTROMAGNETIC TRANSITIONS*

E. M. Henley and B. A. Jacobsohn

University of Washington, Seattle, Washington
(Received 14 March 1966)

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NUCLEAR PARITY VIOLATION TESTS OF NON-LEPTONIC WEAK CURRENTS

E. M. HENLEY *
CERN, Geneva

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Parity-violating asymmetry in nucleon-nucleon scattering*

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Lawrence Livermore Laboratory, Livermore, California 94550

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Physics Department, University of Washington, Seattle, Washington 98195
(Received 20 September 1973)

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CHARGE SYMMETRY BREAKING IN THE NEUTRON-PROTON SYSTEM

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Enhanced *T*-Nonconserving Nuclear Moments

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Nambu–Jona-Lasinio Model and Charge Independence

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(Received 28 September 1988)

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Nucleon and Nuclear Anapole Moments

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Symmetry in physics has been one of Ernie's main interests. He pioneered in this basic field by using nuclei as the tool. His profound knowledge of nuclear physics, joined with his expertise in quantum field theory, make him unique in our profession. This talk is to pay homage to his achievement.

PACS Indices: 25.75+r (Relativistic heavy-ion collisions); 24.80Dc (Symmetries in nuclear processes); 24.85+p (Quarks, gluons, and QCD in nuclei and nuclear processes).

1 Symmetries and Asymmetries

Much of our thinking in modern physics is based on symmetry Quantum Chromodynamics for the strong interaction, the $SU(2) \times U(1)$ Standard Model of elcctroweak forces and General Relativity for gravitation all have their foundations in invariances under certain gauge or coordinate transformations. Yet this beautiful theoretical superstructure of symmetry is in sharp contrast to the stark reality of symmetry violations that have been experimentally observed. Ever since the discovery of parity nonconservation more than thirty-five years ago, many of the other quantum numbers associated with symmetries also have been found to be violated.

Our usual explanation for this apparent contradiction is to invoke spontaneous symmetry-breaking. We assume that the physical laws remain symmetric, but our vacuum state does not. With an asymmetrical vacuum, it follows that our physical world also cannot be symmetric. In this view, the vacuum is regarded as a condensate, analogous to the ground state of a superconductor [l]. If so, as in a superconductor there can be phase transitions of the vacuum through either heating or increasing the baryon density over a large volume.

According to this concept, the system of elementary particles no longer forms a selfcontained unit. The microscopic particle physics depends on the coherent properties of the macroscopic world, represented by the appropriate operator averages in the physical vacuum state.

This is a rather startling conclusion, contrary to the traditional view of particle physics which holds that the microscopic world can be regarded as an isolated system. To a very good approximation it is separate and uninfluenced by the macroscopic world at large. Now, however, we need these vacuum averages; they are due to some long-range ordering in the state vectors. At present our theoretical technique for handling such coherent effects is far from being developed. Each of these vacuum averages appears as an independent parameter, and that accounts for the large number of constants needed in the present theoretical formulation.

On the experimental side, there has hardly been any direct investigation of these coherent phenomena. This is because hitherto in most high-energy experiments, the higher the energy the smaller has been the spatial region we are able to examine. On the other hand, the heavy nuclei naturally provide a testing ground for these ideas.

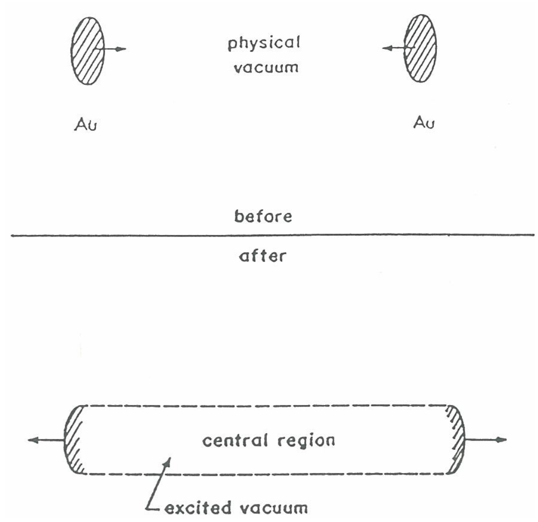


Fig. 1: *Vacuum excitation throuth relativistic heavy ion collision.*

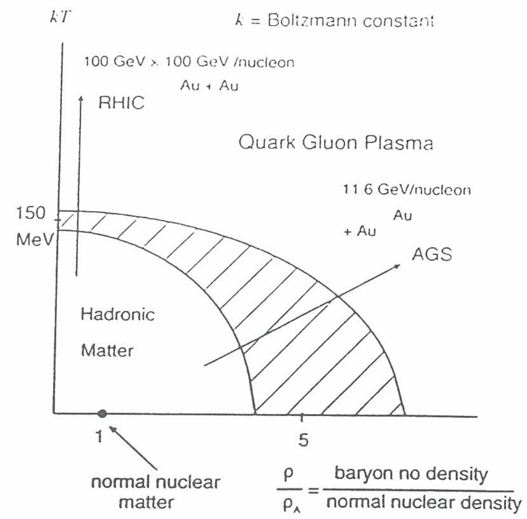


Fig. 2: *Phase diagram in the* $(\kappa T, \rho/\rho_A)$ *plane.*

2 Relativistic Heavy Ion Collisions (RHIC)

2.1 How to Excite the Vacuum?

In order to explore physics in this fundamental area, relativistic heavy ion collisions offer an important new direction [2]. The basic idea is to collide heavy ions, say gold on gold, at an ultra-relativistic region. Before the collision, the vacuum between the ions is the usual physical vacuum; at a sufficiently high energy, after the collision almost all of the baryon numbers are in the forward and backward regions (in the center-of-mass system). The central region is essentially free of baryons and, for a short duration, it is of a much higher energy density than the physical vacuum. Therefore, the central region could become the excited vacuum (Fig. 1).

As we shall see, we need RHIC, the 100 GeV × 100 GeV (per nucleon) relativistic heavy ion collider at the Brookhaven National Laboratory, to explore the QCD vacuum.

2.2 Phase Transition of the Vacuum

A normal nucleus of baryon number A has an average radius $r_A \approx 1.2A^{\frac{1}{3}} fm$ and an average energy density

$$\varepsilon_A \approx \frac{m_A}{(4\pi/3)r_A^3} \approx 130\,\mathrm{MeV}/fm^3. \qquad (1)$$

Each of the A nucleons inside the nucleus can be viewed as a smaller bag which contains three relativistic quarks inside; the nucleon radius is $r_N \approx 0.8 fm$ and its average energy density is

$$\varepsilon_N \approx \frac{m_N}{(4\pi/3)r_N^3} \approx 440\,\mathrm{MeV}/fm^3. \qquad (2)$$

Consequently, even without any sophisticated theoretical analysis we expect the QCD phase diagram to be of the form given by Fig. 2.

In Fig. 2, the ordinate is κT (κ = Boltzmann constant, T = temperature), the abscissa is ρ/ρ_A(ρ = nucleon density, ρ_A = average nucleon density in a normal nucleus A) and the dot denotes the configuration of a typical nucleus A. The scale can be estimated by noting that the critical $\kappa T \sim$ 150-300 MeV is about $\frac{1}{2}-1$ times fm^3 times the difference $\varepsilon_N - \varepsilon_A$, and the critical $\rho/\rho_A \sim$ 4-8 is in the range of l-2 times $(r_A/r_N)^3 \approx (1.2/0.8)^3$.

Accurate theoretical calculation exists only for pure lattice QCD (i.e., without dynamical quarks [3]). The result is shown in Fig. 3.

If one assumes scaling, then the phase transition in pure QCD (zero baryon number, $\rho = 0$) occurs at $\kappa T \sim 150$ MeV with the energy density of the gluon plasma.

$$\varepsilon_P \sim 3\ \mathrm{GeV}/fm^3, \qquad (3)$$

because of the large latent heat, To explore this phase transition in a relativistic heavy ion collision, we must examine the central region. Since

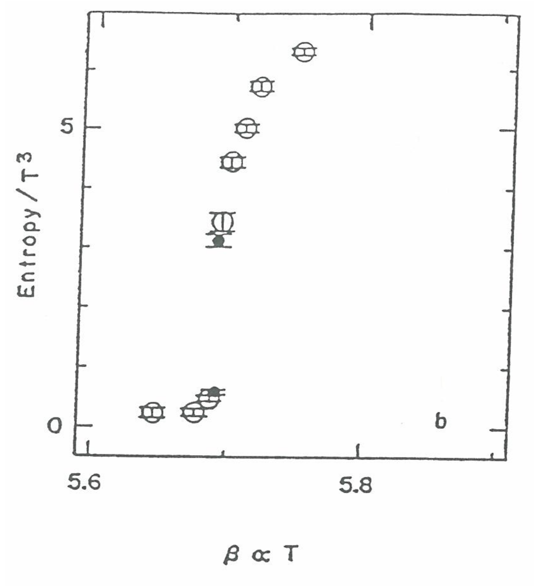


Fig. 3: *Phase transition [3] (pure QCD).*

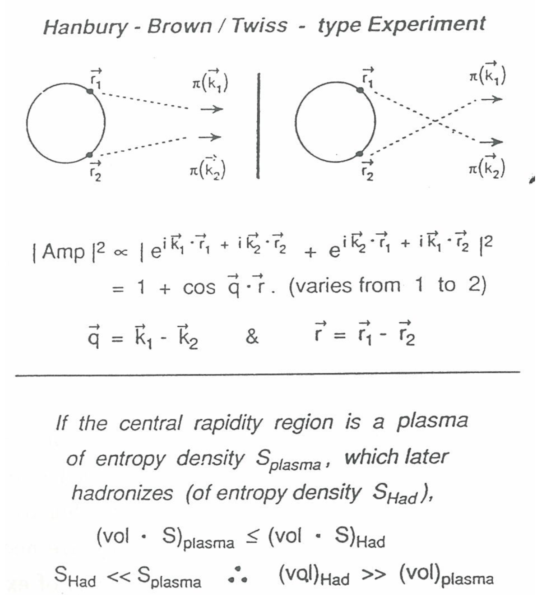


Fig. 4: *Hanbury-Brown-Twiss-type experiment.*

Table 1: $\pi\pi$-interference result [4] from the collision of an O beam (200 GeV/nucleon) on a stationary Au target.

	Rapidity Interval	$R_T(fm)$	Gaussian $R_L(fm)$	Λ
	$1 < y < 2$	4.3 ± 0.6	2.6 ± 0.6	$0.34^{+0.09}_{-0.06}$
		$R_T^{side} = 4.0 \pm 1.0fm$	2.6 ± 0.6	$0.34^{+0.09}_{-0.06}$
Central		$R_T^{out} = 4.4 \pm 1.0fm$	2.6 ± 0.6	$0.34^{+0.09}_{-0.06}$
region	$2 < Y < 3$	8.1 ± 1.6	$5.6^{+1.2}_{-0.8}$	0.77 ± 0.19
(mid-		$R_T^{side} = 6.6 \pm 1.8fm$	$5.6^{+1.2}_{-0.8}$	0.77 ± 0.19
rapidity)		$R_T^{out} = 11.2 \pm 2.3fm$	$5.6^{+1.2}_{-0.8}$	0.77 ± 0.19

$R(\text{Oxygen}) \cong 3fm$

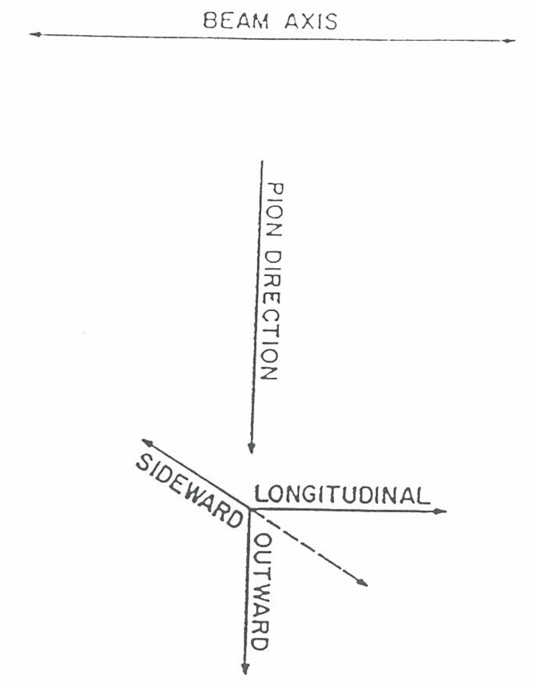


Fig. 5: *Experimental configuration for $\pi - \pi$ interferometry.*

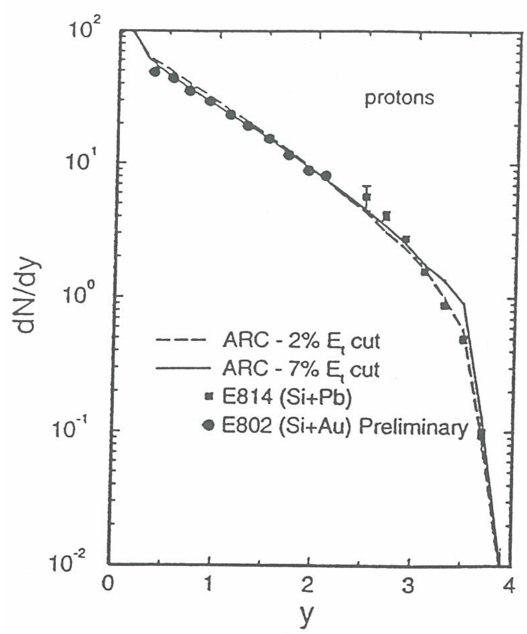


Fig. 6: *The proton rapidity spectra from ARC [5], for two centrality cuts, 2% (solid line) and 7% (dashed line), compared with E802 [9-10] for Si + Au, and E814 [7-8] for Si + Pb.*

only a small fraction of the total energy is retained in the central region, it is necessary to have a beam energy (per nucleon) at least an order of magnitude larger than $\varepsilon_N \times (1.2fm)^3 \sim 5$ GeV; this makes it necessary to have an ion collider of about 100 GeV $\times$ 100 GeV (per nucleon) for the study of the QCD vacuum.

Another reason is that at 100 GeV $\times$ 100 GeV the heavy nuclei are almost transparent, leaving the central region (in Fig. 1) to be one almost without any baryon number. As remarked before, this makes it an ideal situation for the study of the excited vacuum. Suppose that the central region does become a quark-gluon plasma. How can we detect it? This will be discussed in the following.

2.3 Hanbury-Broun-Twiss Type Experiments

As shown in Fig. 4, the emission amplitude of two pions of the same charge with momenta $\vec{k}_1$ and $\vec{k}_2$ from points $\vec{r}_1$ and $\vec{r}_2$ is proportional to

$$A \equiv e^{i\vec{k}_1\cdot\vec{r}_1+i\vec{k}_2\cdot\vec{r}_2} + e^{i\vec{k}_2\cdot\vec{r}_1+i\vec{k}_1\cdot\vec{r}_2}, \tag{4}$$

because of Bose statistics. Let

$$\vec{q} \equiv \vec{k}_1 - \vec{k}_2 \quad \textit{and} \quad \vec{r}_1 \equiv \vec{r}_1 - \vec{r}_2. \tag{5}$$

Since

$$|A|^2 \equiv 1 + \cos\vec{q}\cdot\vec{r} \tag{6}$$

changes from $|A|^2 = 2$ as $\vec{q} \to 0$, to $|A|^2 = 1$ as $\vec{q} = \infty$, a measurement of the $\pi\pi$ correlation gives a determination of the geometrical size R of the region that emits these pions, like the Hanbury-Brown-Twiss determination of the stellar radius.

Now, if the central region is a plasma of entropy density S_p occupying a volume V_p, which later hadronizes to ordinary hadronic matter (of entropy density S_H and volume V_H), the total final entropy $S_H V_H$ must be larger than the total initial entropy $S_P V_P$, because of the second law of thermodynamics. Since $S_P > S_H$, we have

$$V_H > V_P. \tag{7}$$

The experimental configurations and results [4] are given in Fig. 5 and Table 1. One sees that the hadronization radius in the central region is indeed much larger than that in the fragmentation region. Of course, we are far from being able to make any conclusion about the quark-gluon plasma. Much work and higher energy are needed. Nevertheless, it does show that relativistic heavy ions can be an effective means of exploring the structure of the vacuum.

3 Application of the Relativistic Boltzmann Equation

An alternative possibility to generate the quark-gluon plasma is to increase the nuclear density. This approach is being explored at the AGS (Alternating Gradient Synchrotron) at Brookhaven, as indicated in Fig. 2. In this case, there are a large number of hadrons present throughout the entire collision process. Before any conclusion can be drawn about the exotic state of quark-gluon plasma, one must first address the problem of normal hadronic collisions. An ideal method for examining this complex situation is to apply the relativisitc Boltzmann equation:

$$\begin{aligned} & p^\mu \partial_\mu W_a(\vec{x}, t, \vec{p}) \\ = & \sum_n \sum_{b_1, b_2, \cdots, b_n} \int \prod_{i=1}^{n} \frac{d^3 \vec{p}_{b_i}}{(2\pi)^3 2E_{b_i}} W_{b_i}(\vec{x}, t, \vec{p}_{b_i}) \\ & \cdot \sum_m \sum_{c_1, c_2, \cdots, c_m} \int \prod_{j=1}^{m} \frac{d^3 \vec{p}_{c_j}}{(2\pi)^3 2E_{c_j}} |A_{n\to m}|^2 \\ & \cdot (2\pi)^4 \delta^4 \left(\sum_{i=1}^{n} p_{b_i} - \sum_{j=1}^{m} p_{c_j} \right) \\ & \cdot \left[- \sum_{i=1}^{n} \delta_{ab_i} \delta^3(\vec{p} - \vec{p}_{b_i}) \right. \\ & \left. + \sum_{j=1}^{m} \delta_{ac_j} \delta^3(\vec{p} - \vec{p}_{c_j}) \right], \qquad (8) \end{aligned}$$

where $W_a(\vec{x}, t, \vec{p})$ is the probability distribution for hadron species

$$a = p, n, \pi, K, \rho, \Delta, \Lambda, \Sigma, \cdots \qquad (9)$$

and the elements of the S-matrix are given by

$$\begin{aligned} & \langle c_1, c_2, \cdots, c_m | S | b_1, b_2, \cdots, b_n \rangle \\ = \; & A_{n\to m} (2\pi)^4 \delta^4 \left(\sum_{i=1}^{n} p_{b_i} - \sum_{j=1}^{m} p_{c_i} \right). \qquad (10) \end{aligned}$$

Because of the great variety of hadron species, it is not easy to solve the Boltzmann equation. An effective numerical method is the relativistic cascade (ARC) model.

3.1 ARC Model

The ARC model [5] is described in Table 2. Because of the use of a nonzero impact parameter

$$d = \sqrt{\sigma/\pi}, \qquad (11)$$

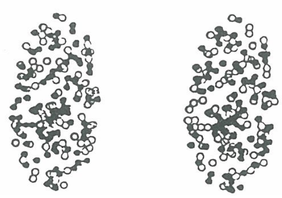
it raises questions of Lorentz invariance which we shall now address.

3.2 Relativistic Invariance of the ARC Model

Decompose each hadron into a very large number λ of partons, say $\lambda = 10^9$. Thus, we regard the initial state of Au + Au as that of 197×10^9 nucleon-partons colliding with 197×10^9 nucleon-partons. Apply the cascade code of Table 2

Table 2: Computational steps of the ARC model [5].

Cascade (*ARC*)
1. Initial condition
$\mathcal{W}_a(\vec{x}, t, \vec{p})$
$= \sum_i \delta^3(\vec{x} - \vec{x}_i(t)) \delta^3(\vec{p} - \vec{p}_i)$
2. Straight line trajectories
$\vec{v}_i = \frac{\vec{p}_i}{E_i}$
$\vec{x}_i(t) = \vec{x}_i(0) + \vec{v}_i t$
3. Collision at closest approach
$d \leq \sqrt{\frac{\sigma_{total}}{\pi}}$
4. Outgoing channel selection
partial cross-sections:
elastic, inelastic (productions of pion, kaon,$\cdots$)
5. Momentum distribution
$\int d(\mathrm{phase-space}) |A|^2$
Repeat steps 2-5



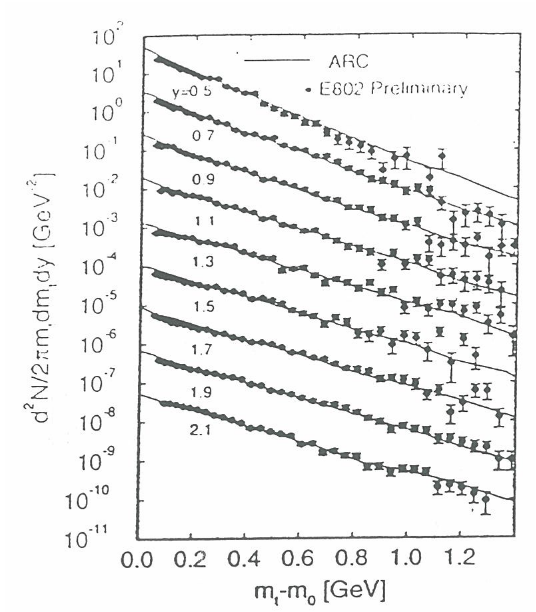


Fig. 7: *E802 [9-10] and ARC proton-m_t spectra for Si + Au in many rapidity bins, at 14.6 GeV/c. Successive rapidity bins are scaled by 10^{-1} for clarity, The lines join ARC points.*

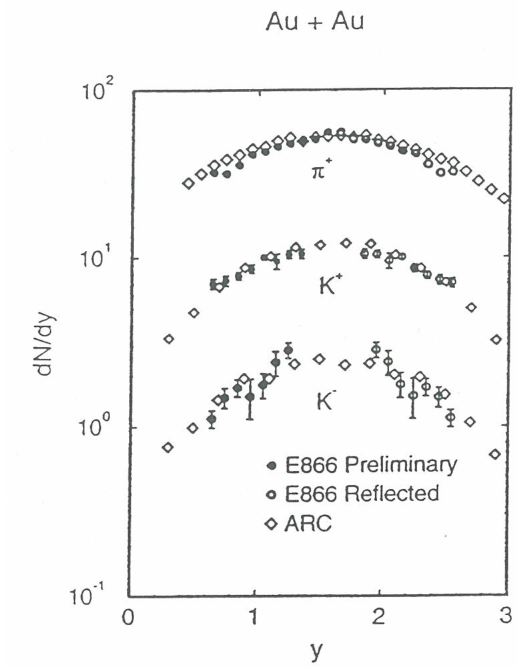


Fig. 8: *Theoretical calculations from ARC [5] compared with experimental results [11] for the rapidity spectra of π^+, K^+ and K^- in Au + Au collisiotls.*

to these partons and replace the usual hadron-hadron collisions by reactions

$$\begin{aligned} & \text{nucleon-parton} + \text{nucleon-parton} \\ \to\ & \text{nucleon-partons} + \text{nucleon-parton} \\ & +\pi - \text{partons} + K - \text{partons}, \end{aligned} \tag{12}$$

$$\begin{aligned} & \pi - \text{parton} + \text{nucleon} - \text{parton} \\ \to\ & \Delta - \text{parton} + \pi - \text{partons}, \end{aligned} \tag{13}$$

etc., the final state may consist of several thousand $\times 10^9$ hadron-partons, whose distribution functions can be converted back to those of the usual hadrons by a division of $\lambda = 10^9$. As we shall see, the ARC model is Lorentz invariant [6] in the limit $\lambda \to \infty$.

Let $W_{aP}(\bar{x}, t, \vec{p})$ be the Boltzmann distribution function of partons of species a, whose integral over the phase space is equal to the total number of a-partons, and let $W_a(\bar{x}, t, \vec{p})$ be that of the "parent" hadron of the same species. As we increase the number of partons per hadron from 1 to λ, the Boltzmann distribution function changes from

$$W_a \to W_{aP} = \lambda W_a. \tag{14}$$

Correspondingly, the binary cross-section varies from σ (the original hadron cross-section) to σ_p (the parton cross-section):

$$\sigma \to \sigma_P = \sigma/\lambda. \tag{15}$$

As a result, the mean free path of the a-parton

$$\ell = W_{aP^{\sigma}P} = W_{a^{\sigma}}$$

remains the same as its "parent" hadron. On the other hand the impact parameter for a parton-parton collision $d_P = \sqrt{\sigma_P/\pi}$, as $\lambda \to \infty$, approaches zero:

$$d \to d_P = d/\sqrt{\lambda} \to 0. \tag{16}$$

Thus,

ARC model $\to$ relativistic Boltzmann equation,

which is invariant under the scale transformation (14)-(15). The theoretical results and predictions of the ARC model are in very good agreement with AGS experiments [7-11], as shown in Figs. 6-8. This also means that the quark-gluon plasma is not yet discovered, and we have to continue in our search for vacuum excitations.

4 Remarks

As we look into the future, the completion of RHIC in 1999 offers an exciting opportunity for nuclear physicists directly to test the very foundation of symmetries and asymmetries, a puzzle that has confronted all particle physicists. In this connection, it may be worthwhile to recall that. From the 1930s to the fifties, nuclear physics was the dominant research arena of fundamental physics; particle physics was then still in its infancy and drew most of its ideas from nuclear physics. Now, near the end of the century, through relativistic heavy ions this will be the case once again.

Acknowledgment

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