

HIGH ENERGY NUCLEUS-NUCLEUS COLLISIONS

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Abstract

Experimental results on high energy nucleus-nucleus interactions are presented. The data are discussed within the framework of standard superposition models and from the point-of-view of the possible formation of new states of matter in heavy ion collisions.

1. Introduction

Collisions of relativistic heavy nuclei have recently become a subject of intense investigation, both experimental and theoretical. It is expected that fundamentally important physical phenomena may occur as a result of the formation of high density and high temperature nuclear matter. Under such extreme conditions matter may transit into the deconfined quark-gluon plasma phase. These conditions existed in the early universe, just a few microseconds after the Big Bang, may be created within neutron stars, and are expected to occur in central heavy ion collisions. The latter gives us a unique opportunity to study these extreme conditions in our laboratories. However, it was soon realized that experimental data are dominated by common features which reflect the Lorentz contraction, kinematical constraints and variations in the impact parameter. Nevertheless, it is believed that new phenomena will not be completely covered by this "standard background."

This paper is organized as follows. In Section 2, I briefly describe the expectations for both conventional and new phenomena. Selected experimental results from studies of high energy nucleus-nucleus interactions are presented in Section 3. In the last Section, I summarize the present stage of investigation of nucleus-nucleus collisions and say a few words about future perspectives.

2. Expectations

2.1. Conventional phenomena

Our predictions for conventional phenomena follow from the study of high energy hadron-nucleus collisions [1]. The main outcome of these studies was the observation of a moderate increase in the number of particles produced in nuclear targets in comparison to the multiplicity of particles produced in a hydrogen target. This 'nuclear transparency' is surprising, at first sight, since in a collision of a hadron with a heavy nucleus, the hadron must penetrate

several mean free paths of nuclear matter. Therefore, we would expect that both the incident hadron and the produced secondaries would undergo multiple scatterings, developing a hadronic shower inside the target nucleus (see Figure 1). The absence of such a shower can be explained by formation zone arguments [2], namely the production of a secondary particle is not an instantaneous process but requires a certain creation time in its rest frame ($\sim 1 \text{ fm}/c$). Due to the time dilation in the laboratory frame, the fast particles are produced outside the nucleus and, therefore, only the incident hadron and the slow secondaries can undergo rescattering inside the target nucleus, as illustrated schematically in Fig. 1.

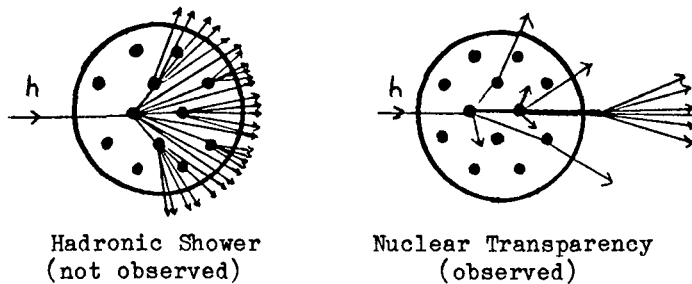


FIGURE 1. Particle production in hadron-nucleus interactions.

The nuclear transparency, along with the additional assumptions that (a) slow particles modify only slightly the observed final state, and (b) the incident hadron (or hadron constituent) undergoes independent collisions inside the nucleus, represent the basic principles of the so called Superposition Models [3], which satisfactorily describe the hadron-nucleus data. All of these models can be extended in a straightforward way to nucleus-nucleus interactions at high energies [4], and we expect that the majority of nucleus-nucleus experimental data may be explained by these conventional models.

2.2. New phenomena

Comprehensive reviews of the expectations of new phenomena which may occur in central nucleus-nucleus collisions have been published [5]. In the limited space available only a very general coverage of this topic is possible.

When two large nuclei collide centrally at high energies, they pass through one another and in the central region between the two, now receding, nuclei dense nuclear matter may be formed. If the density exceeds some critical value, the nuclear matter may transit into the deconfined phase of quarks and gluons (see Fig. 2). Different theories and models (e.g. relativistic hydrodynamics, transport theory, QCD Monte Carlo calculations on the lattice, etc.) have been applied to describe the phenomena occurring in the head-on collision of two such compound objects as heavy nuclei. All of them agree that at energy densities exceeding $2 \text{ GeV}/\text{fm}^3$ a transition to the quark-gluon plasma is likely to occur. There still remain many theoretically unresolved problems, mainly connected with the

stability of the solutions, but it is believed that the transition will effect the spectra and the composition of final state particles. However, bearing in mind the unresolved problems, one has to be cautious in considering the experimental observables and signatures.

Now I proceed further with the discussion of diagnostic tools to study the quark-gluon plasma. Among the possible hadronic signals, we expect high multiplicities of produced particles, an enhanced ratio of strange to nonstrange particles, high average transverse momenta and unusual event structure, e.g. rapidity fluctuations. The leptonic signals, such as direct photons emitted as plasma electromagnetic radiation and direct dileptons produced in quark-antiquark annihilation, will provide information about the early stage of plasma formation, particularly the plasma temperature. Additionally, one can expect that any correlations between hadronic and leptonic signals may be considered as experimental triggers for a quark-gluon plasma.

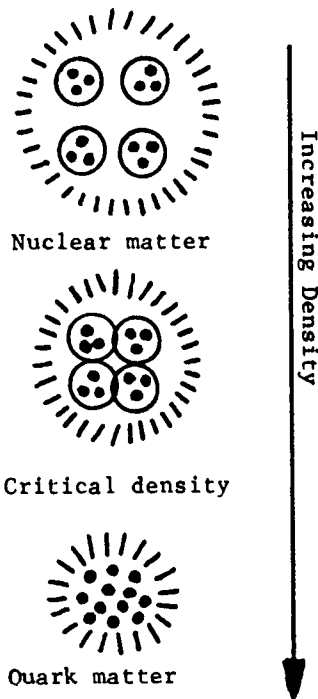


Figure 2. Transition to the quark matter phase.

3. Experiment

The systematic study of nucleus-nucleus collisions are presently limited to laboratory energies of about 4 GeV/nucleon at accelerators. The data on cosmic ray nuclei with energies 20 - 65 GeV/nucleon have been reported recently from a hybrid electronic counter-emulsion chamber experiment [6]. A systematic analysis of cosmic ray interactions with mean energy of 20 GeV/nucleon averaged over the rapidly falling energy spectrum, are also available [7]. At energies above 100 GeV/nucleon one can analyze only single cosmic ray events recorded in emulsion chambers. For these highest energies, I will present data obtained in a series of balloon flights by the JACRE collaboration.

3.1. Inclusive data

As I said at the beginning, we expect that inclusive nucleus-nucleus data can be explained within the framework of superposition models. I show only one example as an illustration that these models do describe the experimental inclusive data. It is expected that in nucleus-nucleus collisions the distribution of the number of produced particles will be very wide due to the large range of variation of the impact parameters. Different superposition models [4] predict

that the ratio of the dispersion, D , to the average multiplicity \bar{N} will be about twice as large as the same ratio for proton-nucleus interactions. In Figure 3, the dependence of D on the average multiplicity \bar{N} , is displayed. The shaded area represents the prediction of superposition models ($D/\bar{N} = 0.8 - 1.3$ depending upon the model), and points with error bars are the experimental data for

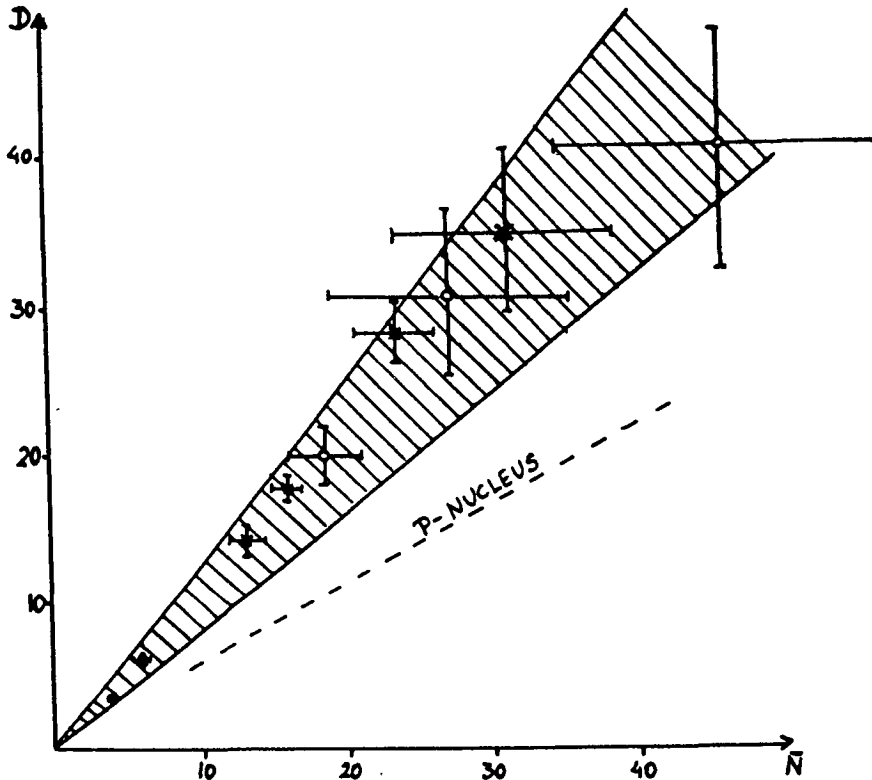


Figure 3. Dependence of the dispersion of the multiplicity distribution on its average value. Points are ● - 3.7 GeV/n ^{22}Ne interactions in emulsion [9], ○ - 35 GeV/n ^{56}Fe interactions in C, emulsion and Pb [6], and x - $\langle 20$ GeV/n \rangle cosmic ray ($^4\text{He} - ^{56}\text{Fe}$) interactions in emulsion [7].

different projectile and target nuclei and for different primary energies [6,7,9]. The universality of the D/\bar{N} ratio, which depends neither on the energy nor on the target and projectile masses, can be observed in Figure 3. A similar universality was reported for proton-nucleus collisions [10]. The consistency between the experimental data and superposition model predictions is evident in Fig. 3.

However, the inclusive data are dominated by peripheral interactions and we expect that inclusive spectra taken over many events may smear out any information on quark-gluon plasma which may be created only in central collision events.

3.2. Central nucleus-nucleus collisions

The JACEE collaboration has observed several high energy (above 500 GeV/nucleon) nucleus-nucleus interactions, which demonstrate characteristics not expected from what we consider as "standard background." For a better understanding of the data, let me start with a brief description of the procedure for data recording and analysis used in the JACEE experiments. The high energy interactions were recorded in emulsion chambers exposed to the primary cosmic rays in a series of balloon flights [8]. The emulsion chamber is a multilayered detector which serves simultaneously as both target and coordinate/ionization recorder. The vertical configuration of the typical JACEE emulsion chamber is shown in Figure 4. Incident particles are identified in the primary section by means of ionization measurements in the emulsion layers as well as by pit measurements in CR-39 etchable plastics. Charge resolution is typically 1.0 charge unit. The target section contains thin emulsion plates interleaved with acrylic and/or iron sheets. Thick emulsion and CR-39 plates are inserted in the target section to permit the identification of projectile fragments. The following spacer section, used in some chambers, allows photons from π^0 decays to diverge before reaching the calorimeter section, so that individual photon cascades can be observed. The calorimeter contains Pb plates interleaved with emulsion plates and x-ray films. The total thickness of the calorimeter is 5-7 radiation lengths.

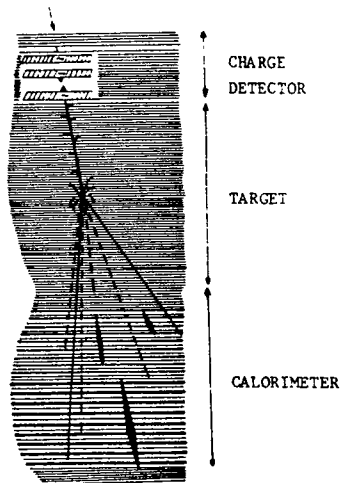


Figure 4. Schematic diagram of a typical JACEE chamber.

Thanks to the high spatial resolution of the emulsion, the hundreds of particles emerging from an interaction vertex can be unambiguously detected. Multiplicities N_{ch} and emission angles of all secondaries are measured in consecutive emulsion plates downstream of the interaction vertex, with a typical error in relative angle measurements of 0.1 - 0.2 pseudorapidity units. In the calorimeter section the emission angles and energies of individual photons are measured, so information on the transverse momenta of photons, with accuracy of $\Delta p_t/p_t = 0.25$, is obtained. The average value of the transverse momentum ($\langle p_t \rangle_\gamma$) for an individual event is estimated by an exponential fit to either the differential or integral distribution of p_t of π^0 meson via: $\langle p_t \rangle_\pi = 2 \langle p_t \rangle_\gamma$. For events with overlapping individual photon showers (interactions in the calorimeter section and the highest energy collisions) $\langle p_t \rangle_0$ is obtained by comparing the three dimensional cascade development with Monte Carlo simulations which use as input the measured pseudorapidity distribution of

charged particles and assume isospin symmetry for pions and an invariant p_t distribution.

For each event the energy densities (ϵ) have been evaluated at the time of 1 fm/c after the collision from the formula proposed by Bjorken [11]:

$$\epsilon = \frac{3}{2} \sqrt{\langle p_t \rangle} \frac{2}{\pi + m_\pi^2} * \frac{dN}{d\eta} * \frac{1}{2\pi A_{\min}} \quad 2/3, \quad (1)$$

where $A_{\min} = \text{Min}(A_{\text{projectile}}, A_{\text{target}})$, $\langle p_t \rangle_\pi$ is the determined transverse momentum of π^0 and $dN/d\eta$ is the measured density of charged particles in the CM pseudorapidity central region ($|\eta| < 1$).

3.2.1 Multiplicities, average transverse momenta & energy densities

In Table 1, the heavy ion interactions with charged particle multiplicities exceeding 400, which may be considered as central collisions, are listed. The observed large multiplicities for these events are consistent with the calculations of the Multi-chain Model [4c] for collisions with impact parameter $b=0$. The average transverse momenta exhibit high values compared to the values interpolated from CERN ISR and SPS collider experiments [12]. For the events listed, the energy densities are above 2 GeV/fm³.

Table I. High multiplicity events ($N_{\text{ch}} > 400$) in JACEE.

Event Type	E_0^0 (TeV/n)	N_{ch}	$\langle p_t \rangle_\pi$ (GeV/c)	$dN/d\eta$	ϵ (GeV/fm ³)
Ca+Pb	1.5	1050 ⁺³⁰⁰ ₋₅₀	0.55±0.10	258±12	3.0
Si+AgBr	4.1	1010±30	0.55±0.10	183±10	2.7
Ca+C	100.0	760±30	0.53±0.04	81±10	2.0
Ca+Pb	0.5	670±40	(1.03)	142±8	(3.0)
Ca+Pb	1.8	457	(2.1±0.1)	100±16	(4.3)
Ar+Pb	1.0	416	1.2±0.2	134±8	3.3

*Values in () require further experimental checking.

3.2.2. Rapidity fluctuations

Figure 5 shows the CM pseudorapidity distribution of the high multiplicity Si+AgBr event. This large multiplicity is consistent with the predictions of the Multi-Chain Model, but we observe a rich structure in the pseudorapidity spectrum and the question we want to answer is "Are the observed fluctuations purely statistical, i.e. due to the fine binning of the data, or are they of physical origin and, for example, may be related to the expected violent cooling of a quark-gluon plasma?"

It is not a simple task to answer this question, since we do not know in advance the distribution of the real event. Various methods have been applied to identify nonstatistical fluctuations in the pseudorapidity and azimuthal angle distributions [13]. In a recently published paper [14], the dependence of factorial moments of the rapidity distribution on the size $\delta\eta$ of the η resolution was studied. Figure 6 shows the scaled factorial moment $\langle F_5 \rangle$

versus $\delta\eta$ on a logarithmic scale. The moments, computed from the measured pseudorapidity distribution of the event on Figure 5, in the interval $-3.55 < \eta < 3.65$ are marked by dots in Fig. 6. A general tendency for $\langle F_5 \rangle$ to increase with decreasing $\delta\eta$ is

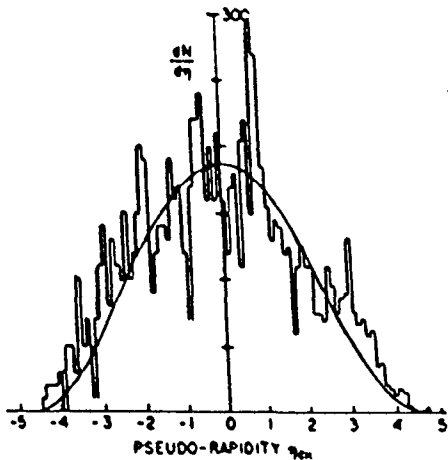


Figure 5. The pseudorapidity distribution for the Si+AgBr event.

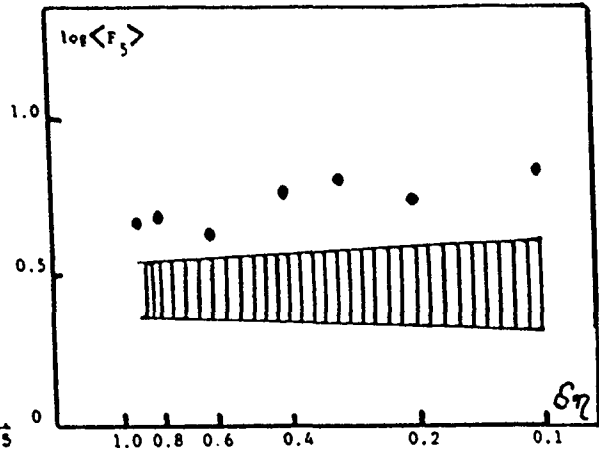


Figure 6. $\log \langle F_5 \rangle$ [14] for the event Si+AgBr.

observed. For comparison the moments simulated from a smooth pseudorapidity distribution with purely statistical fluctuations are shown in Fig. 6 as the shaded area. One sees clearly that the data lie well above the predictions for a smooth pseudorapidity distribution.

Other methods have also been used to study the fluctuations, for example, Takagi [15] applied power spectrum analysis or Chebyshev expansions to three of the high multiplicity nucleus-nucleus events observed by JACEE. He concluded that there was fairly strong evidence in favor of non-statistical fluctuations in the analysed events.

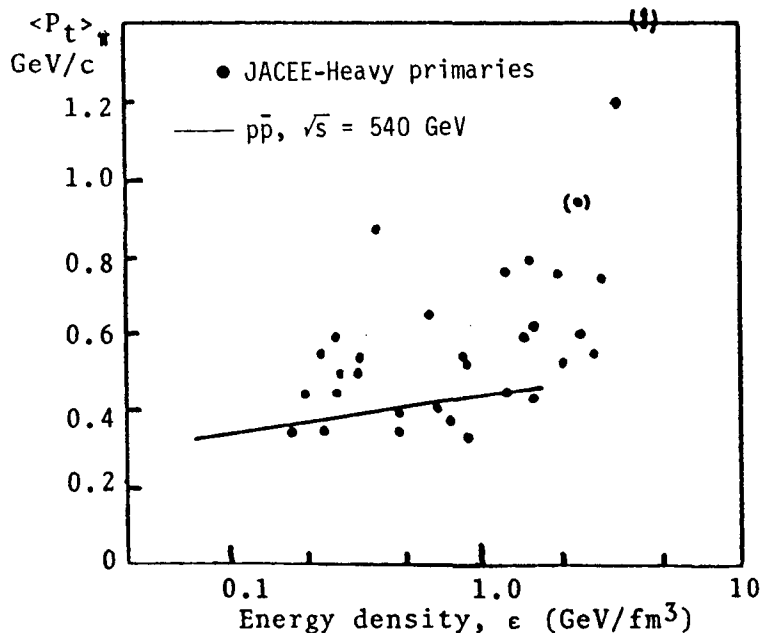


Figure 7. Correlation between transverse momentum and energy density.

3.2.3. Correlation of $\langle p_t \rangle$ with the energy density

In Figure 7 the correlation between $\langle p_t \rangle_\pi$ and the energy density for individual nucleus-nucleus interactions is displayed. For comparison the data from the $p\bar{p}$ collider at 150 TeV from the UAL group are shown [12]. The $p\bar{p}$ rapidity density data were converted to an energy density by taking $A_{\min} = 1$ in Eq. (1). As seen on Figure 7, the $p\bar{p}$ data do not show energy densities higher than $2 \text{ GeV}/\text{fm}^3$. The increase of $\langle p_t \rangle_\pi$ with energy density for the $p\bar{p}$ data can be satisfactorily explained by the contribution of low p_t ($< 5 \text{ GeV}/c$) QCD jets and is not related to quark-gluon plasma formation. The JACEE nucleus-nucleus data are widely dispersed on Figure 7, but it appears that the growth of $\langle p_t \rangle$ with increasing energy density is faster than in $p\bar{p}$ data. In addition, above $2 \text{ GeV}/\text{fm}^3$ the slope changes even more rapidly. This increase cannot be explained by any conventional considerations, for example multiple scattering or contributions from QCD mini-jets. On the other hand, the statistics for the events of the greatest interest ($\epsilon > 2 \text{ GeV}/\text{fm}^3$) are still low, and any interpretation of the observed increase in $\langle p_t \rangle$ as the formation of new states of matter can only be regarded as speculative at the present stage.

4. Summary

Experimental results on nucleus-nucleus interactions show that the inclusive data, as well as the large multiplicities of produced particles in central collisions, are consistent with conventional superposition models. On the other hand, there are data such as the observations of high $\langle p_t \rangle$, nonstatistical pseudorapidity fluctuations, and the growth of $\langle p_t \rangle$ with energy density which cannot be described in the framework of standard superposition models. Although these results cannot be definitely interpreted as quark-gluon plasma formation, they encourage us to continue the search for new states of matter in nucleus-nucleus collisions.

There are still problems which need further exploration both theoretically

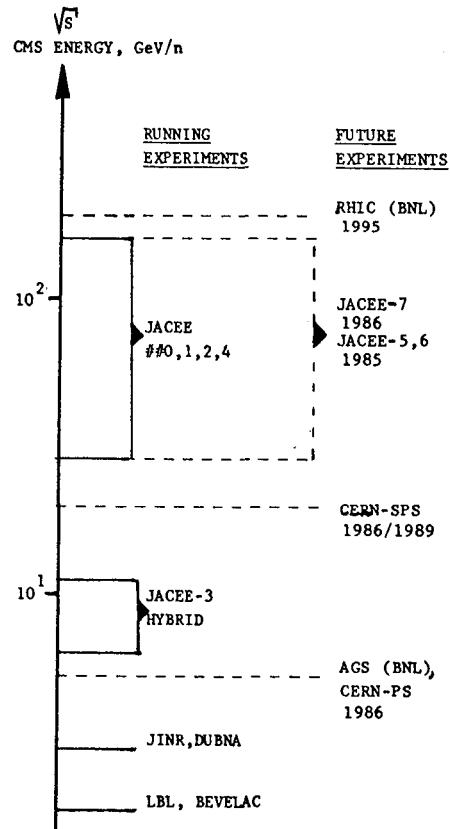


Figure 8. Current and Future Experiments.

and experimentally. Theoretically a better understanding of the stability of solutions and more precise predictions for both conventional and new physics are needed. On the experimental side we need to increase the primary energy, extend the range of available masses of colliding nuclei and enlarge the event statistics. The development of new heavy ion accelerators at Brookhaven and CERN together with the proposed experiments searching for specific quark-gluon plasma signatures will be extremely interesting. In Figure 8, I schematically display the energy range covered by presently working accelerators/experiments as well as future possibilities.

I would like to end my talk concluding that although the present situation is still not clear, we can expect that in the future we shall learn a lot about fundamentally important problems of hadron physics.

Acknowledgements

The author thanks Dr. R. Holynski for valuable discussions and many helpful comments in the preparation of the talk and Dr. J. P. Wefel for a critical reading of this manuscript. This work is supported, in part, at LSU by NSF grant PHY-8304003.

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