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OBSERVATION OF DECONFINEMENT PHASE TRANSITION IN NUCLEUS–NUCLEUS COLLISIONS *

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The main results obtained within the energy scan program at the CERN SPS are presented. The anomalies in energy dependence of hadron production indicate that the onset of deconfinement phase transition is located at about 30 A GeV. For the first time we seem to have clear evidence for the existence of a deconfined state of matter in nature.

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In the mid 1990s a study of results from experiments at CERN (with a collision energy in the centre of mass of the nucleon–nucleon pair of $\sqrt{s}_{NN} = 20$ GeV) and the Alternating Gradient Synchrotron (AGS) at BNL (maximum energy $\sqrt{s}_{NN} \approx 5.5$ GeV) indicated [1, 2] intriguing changes in the energy dependence of hadron production between top AGS and CERN SPS energies. Within a statistical model of the early stage of the collision process [3] these changes can be attributed to the onset of the deconfinement phase transition, *i.e.* creation of a new state of matter in which quarks and gluons are no longer confined with hadrons [4]. The model predicted a sharp maximum in the multiplicity ratio of strange hadrons (hadrons which contain strange s and anti-strange $\overline{s}$ quarks) to pions (the lightest hadron) at the beginning of the transition region, at about $\sqrt{s}_{NN} \approx 7.5$ GeV. This prediction triggered a new experimental program at the SPS — the energy scan program [5]. Within this program head-on (central) collisions of two lead nuclei (Pb + Pb) at several energies ($\sqrt{s}_{NN} = 6.3$, 7.6, 8.7 and 12.3 GeV) were registered by the NA49 experiment. Other heavy ion experiments at the SPS (NA45, NA50, NA57 and NA60) participated in selected runs of this program.

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Recently published results from this program, obtained mainly by the NA49 collaboration [6, 7], confirmed expectations: rapid changes of hadron production properties occur within a narrow energy range of $\sqrt{s}_{NN}$ = 7–12 GeV.

The top panel of Fig. 1 shows that the number of pions produced per nucleon participating in the collision increases with energy as expected in both proton–proton and nucleus–nucleus reactions. However, the rate of increase in nucleus–nucleus collisions becomes larger within the SPS energy range and then stays constant up to the RHIC domain.

The most dramatic effect is seen in the energy dependence of the ratio $\langle K^+\rangle/\langle\pi^+\rangle$ of the mean multiplicities of K^+ and π^+ produced per event in central Pb + Pb collisions, which is plotted in the middle panel of Fig. 1. Following a fast threshold rise, the ratio passes through a sharp maximum in the SPS range and then seems to settle to a lower plateau value at higher energies. Kaons are the lightest strange hadrons and $\langle K^+\rangle$ counts for about half of all the anti-strange quarks produced in the collisions. Thus, the relative strangeness content of the produced matter passes through a sharp maximum at the SPS in nucleus–nucleus collisions. This feature is not observed for proton–proton reactions.

A third important result is the constant value of the apparent temperature of K^+ mesons in central Pb+Pb collisions at low SPS energies as shown in the bottom panel of Fig. 1 [8]. The plateau at the SPS energies is preceeded by a steep rise of the apparent temperature measured at the AGS and followed by a further increase indicated by the RHIC data. Very different behavior is measured in proton–proton interactions [9]

Presently, the sharp maximum and the following plateau in the energy dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio has only been reproduced by the statistical model of the early stage [6]. In this model it reflects the decrease in the number ratio of strange to non-strange degrees of freedom and changes in their masses when deconfinement sets in [3]. Moreover, the observed steepening of the increase in pion production is consistent with the expected excitation of the quark and gluon degrees of freedom. Finally, in the picture of the expanding fireball, the apparent temperature is related to the thermal motion of the particles and their collective expansion velocity. Collective expansion effects are expected to be important only in heavy ion collisions as they result from the pressure generated in the dense interacting matter. The stationary value of the apparent temperature of K^+ mesons may thus indicate an approximate constancy of the early stage temperature and pressure in the SPS energy range due to the coexistence of hadronic and deconfined phases [8, 10].

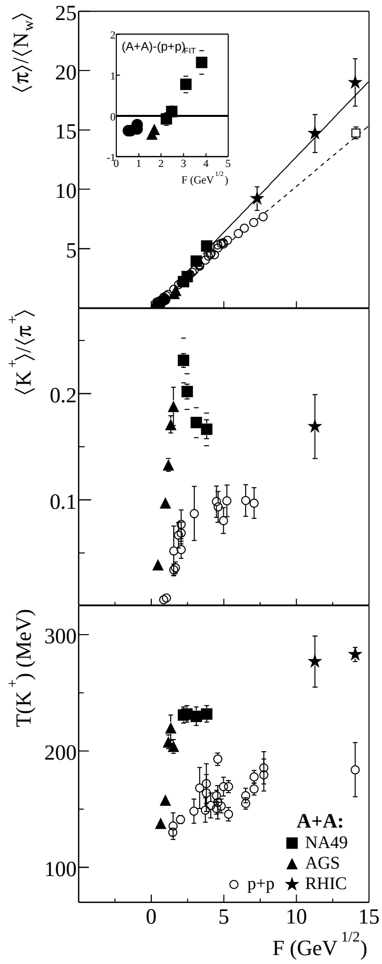

Fig. 1. Collision energy dependence ($F \equiv (\sqrt{s_{NN}} - 2m_N)^{3/4}/\sqrt{s_{NN}}^{1/4} \approx s_{NN}^{1/4}$, where m_N is nucleon mass) of various hadron production properties (for details see text) measured in central Pb + Pb and Au + Au collisions (solid symbols) compared to results from $p+p$ reactions (open dots). The changes in the SPS energy range (solid squares) suggest the onset of the deconfinement phase transition.

These results suggest that the deconfinement phase transition exists in nature (and thus the QGP) and that in Pb + Pb collisions it begins to occur in the SPS energy range. From the composition of hadrons resulting from the decay of the fireball one estimates [11] that the temperature at which the transition takes place is $T \approx 2 \times 10^{12}$ K (170 MeV), coinciding with the limiting temperature of hadrons suggested at CERN many years ago by Rolf Hagedorn.

The observation of anomalies in the energy dependence of hadron production in Pb + Pb collisions in the SPS energy range requires further study. Analysis of data taken last year continues in search of further phenomena caused by the deconfinement phase transition, such as anomalies in event-by-event fluctuations [12–14] In the future it is necessary to extend measurements of the energy dependence to central collisions of light nuclei as well as to proton-proton and proton–nucleus interactions. Such measurements should significantly constrain models of the collision process and, in particular, help us to understand the role played by the volume of the droplet of strongly interacting matter in determining the onset of the deconfinment phase transition.

Properties of the hot quark gluon plasma are presently studied at RHIC (see the next article in this issue) and starting from 2008, will be investigated at very high collision energies at the Large Hadron Collider at CERN.

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