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ABSTRACT

Results from CERN experiment NA36 are reported. Cross sections for the production of singly strange particles in the S+Pb and p+Pb reactions have been measured in the rapidity range $1.25<y<3.5$ and for $p_t>0.2$ GeV. A significant difference in the rapidity distributions of the lambda particles originating from these reactions suggests a fundamental difference in the strangeness production mechanism.

Introduction

Quark-Gluon Plasma is frequently called the Holy Grail of contemporary subatomic physics, but such hot and dense matter has long been of great interest to the scientific community, with most of that interest coming from cosmology and astrophysics. It is believed that the universe went through such a phase in the early stage (10^{-6}s)[1]. There are also indications from astrophysics that it could exist in the interior of neutron stars[2]. In order to understand and describe the evolution of such systems a reliable model and equation of state for the nuclear matter were needed. While reviewing early attempts to answer this demand one should not overlook the model provided by Hagedorn more than twenty years ago to describe hot and dense nuclear matter in the context of mesons and nucleons - the statistical bootstrap model[3]. It provided a very useful working model for cosmologists but met with criticism of over-counting particle states and ignoring fundamental physics[4]. Another very interesting approach was presented by T.D. Lee[5], who predicted that under the extreme conditions a phase transition to the abnormal nuclear matter (chiral symmetry restoration) must occur. Unfortunately, he was not able to determine more accurately either the properties of the final state or conditions under which such a transition could take place.

In order to construct more reliable models with greater predictive power more experimental data was needed. However the beginning of the universe does not happen every day. Neither does the collapse of a neutron star. The only way to achieve conditions close to those mentioned above would be by collisions of relativistic heavy nuclei. That is why the experimental program at the Bevalac (synchrotron at the Lawrence Berkeley Laboratory) started in 1974[6].

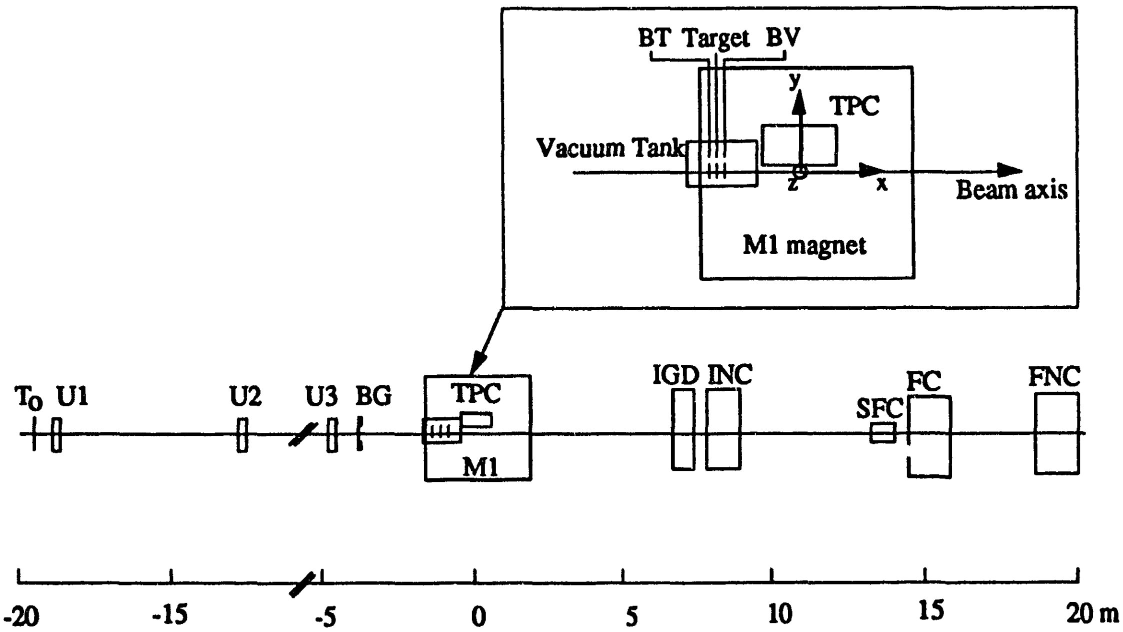
A new approach in studying nuclear matter emerged when the quark model and asymptotically free gauge theories started to attract more and more attention offering a consistent explanation of the hadron spectra and of the strong interactions[7,8]. It also inspired two Cambridge (England) physicists J.C. Collins and M.J. Perry who worked on the equation of state for nuclear matter. They published a paper[4] in Physical Review Letters in 1975 on "Superdense Matter: Neutrons or Asymptotically Free Quarks?". They started from a simple observation that the density of nuclear matter in neutron is $\sim 8*10^{14}$g/cm^3 and that of a neutron star core exceeds $4*10^{15}$g/cm^3 so in such case one must expect the hadrons to overlap. Therefore they suggested that matter at such high density is a quark soup and the identity of the individual hadrons is confused. They realized that the calculations given in that paper were clearly neither complete nor rigorous, but their most important conclusion was that while studying the hot and dense matter the structure of the hadrons must be taken into account.

A few years later (May 1982) more than a hundred physicists gathered on a workshop at Bielefeld[9] to discuss ways of creating the QGP in the laboratory and the possible experimental program to study its properties. During that workshop professor H. Satz was able to say : "Recent developments in QCD provide considerable confidence in the existence of a new phase of matter - the quark-gluon plasma". Thanks to the efforts of many physicists a better-defined picture of the Quark-Gluon Plasma emerged. It became obvious that deconfinement and chiral symmetry restoration would be the most striking features of that new state of matter.

Unfortunately the QCD Lagrangian with a running coupling constant did not offer the possibility of analytical calculations of the phase transition. This led to attempts to obtain numerical predictions on a four-dimensional space-time mesh (lattice QCD). The first calculations were simplistic because the available computing power limited both the size of the lattice and the complexity of the systems that were studied but they strengthened the conviction that energy densities that were needed to produce the QGP could be obtained in the laboratory in the heavy ion collisions[10].

It is one thing to produce a bubble of Quark-Gluon Plasma and another to prove that it was actually produced and determine its properties. Small size (~10fm) and short life time(~10fm/c) of the plasma droplet make it particularly difficult to detect. Additionally the hadronization phase may obscure the possible signal. Various experimental probes have been suggested, some of them more robust than others[11] and strangeness was advocated by Koch, Muller and Rafelski[12] as the most promising one. First of all, the QGP environment even without full chiral symmetry restoration, dramatically reduces the energy threshold for strangeness production (by a factor of two) and the time needed to obtain the equilibration is approximately 30 times shorter for the plasma (10^{-23}s) than for the hadron gas ($3*10^{-22}$s). Moreover, the high density of strange and antistrange quarks may lead to the formation of the multistrange baryons and antibaryons which are otherwise heavily suppressed. So, although the strangeness abundance would be modified during the hadronization, the original effect was thought to be so strong that there is a hope that it would survive. Since predictions were rather uncertain, it is desirable to look at all possible correlations of the quantities mentioned above and correlations of these signatures with global observables like event multiplicity, transverse energy distribution or the zero degree energy flow.

Experimental setup.



T_0	Scintillator	IGD	Intermediate Gamma Detector
U1, U2, U3	Multiwire Proportional Chambers	INC	Intermediate Neutral Calorimeter
BG	Beam Geometry Counters	SFC	Small Forward Čerenkov
BT, BV	Silicon Detectors	FC	Forward Čerenkov
TPC	Time Projection Chamber	FNC	Forward Neutral Calorimeter

Fig. 2. NA36 experimental setup.

The NA36 spectrometer was especially designed to look at the strangeness production[13]. This required a large acceptance and a high two-track resolution. In order to meet that goal a large-volume TPC with a wire read-out was constructed[14]. The ability to record three dimensional information about the collision facilitated event reconstruction in the high track-density environment and the wire readout (1 cm wires with a 2.4 mm pitch) guaranteed good two-track resolution. The detector was placed in a very strong (3T) magnetic field in order to sweep away the low momentum pions and its position, 1 cm above the ion beam avoided having the projectile fragments traversing the chamber (Fig. 1).

The ion beam was defined by a scintillator counter and three wire chambers. Interaction in the target was detected by a pair of silicon counters one just before and one just after the target. A protection circuit against pileup (overlapping events in the TPC) was used so there was a guarantee that only clean events are written to the tape. Since the most interesting physics was expected from the most central events the signal from the forward hadron calorimeter was folded into the trigger to enhance central collisions in the event sample. But the selected trigger mix (45% central events, 45% minimum bias events and 10% beam events) guaranteed that the results could be corrected for the trigger bias and properly normalized so the final differential cross-sections are bias-free.

Asymmetric positioning above the beam favored detection of those V^0's for which the softer particle was bent up. In case of the Λ ($\bar{\Lambda}$) one of the decay products is a proton (or anti-proton) and the other one is pion. Because of the mass difference between the proton and the pion, most of the momentum (especially for lower rapidities) is carried by the proton and the magnet polarity is critical to the soft pion detection. Since pions coming from Λ and $\bar{\Lambda}$ have opposite signs the magnet polarity which was good for one kind of particle strongly suppressed the other. In order to compensate for this effect data was taken with both magnet polarities. This approach made it possible to detect and measure with high accuracy the charged products of all the neutral strange particles decays.

A set of p+Pb data was taken for comparison with the same experimental setup and analyzed with the same analysis chain.

Signal extraction

Statistics collected during the August '90 running time is shown in table 1.

Table 1.

Statistics for the '90 run.

target	magnet polarity	statistics (events)
Pb	(+) positive down	$1.4*10^6$
Pb	(-) positive up	$2.2*10^6$
S	(+) positive down	$6.0*10^5$

All the tapes were processed up to the DST level (tracking, V finding and fitting), but since the antistrange baryons were thought to be of most interest, the analysis of the negative polarity sample was completed first. Simple geometric cuts were first applied to filter the reconstructed V^0 candidates and significantly reduce the combinatorial background.

The Podolanski-Armenteros plot for the final sample is shown (Fig. 2.). Thanks to the good statistics and low background a strong and clear signal can be easily seen. The small opening angle for the electron pairs coming from the γ conversion places them at the bottom of the plot and makes them easy to eliminate.

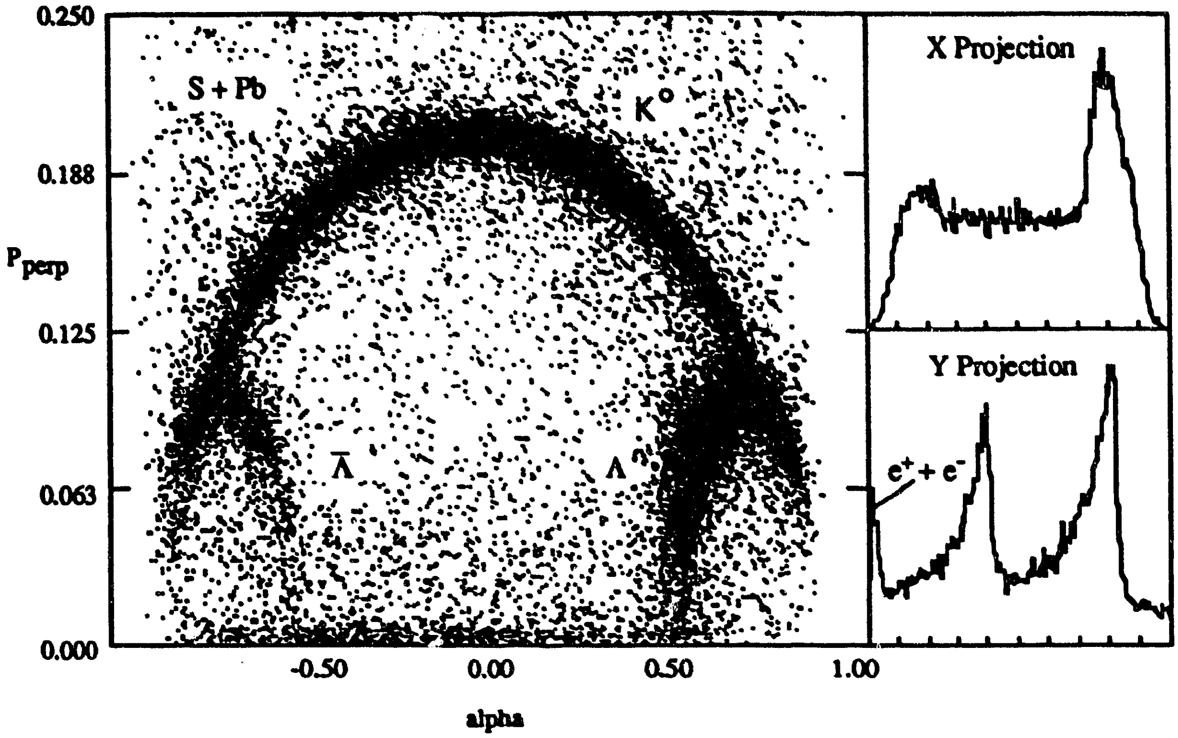


Fig. 2. The Podolanski-Armenteros plot.

The aim of the analysis was to obtain differential production cross sections for Λ, o(Λ, ‾) and K^0 as a function of multiplicity, rapidity and transverse momentum. The appropriate binning was selected based upon the available statistics and a requirement that the background subtraction should be unambiguous. Each bin was corrected separately. First of all a histogram of the effective mass for each bin was generated. All the entries coming from the peripheral events were weighted according to the trigger weight established from the comparison of the peripheral to central events ratio in beam and minimum bias events.

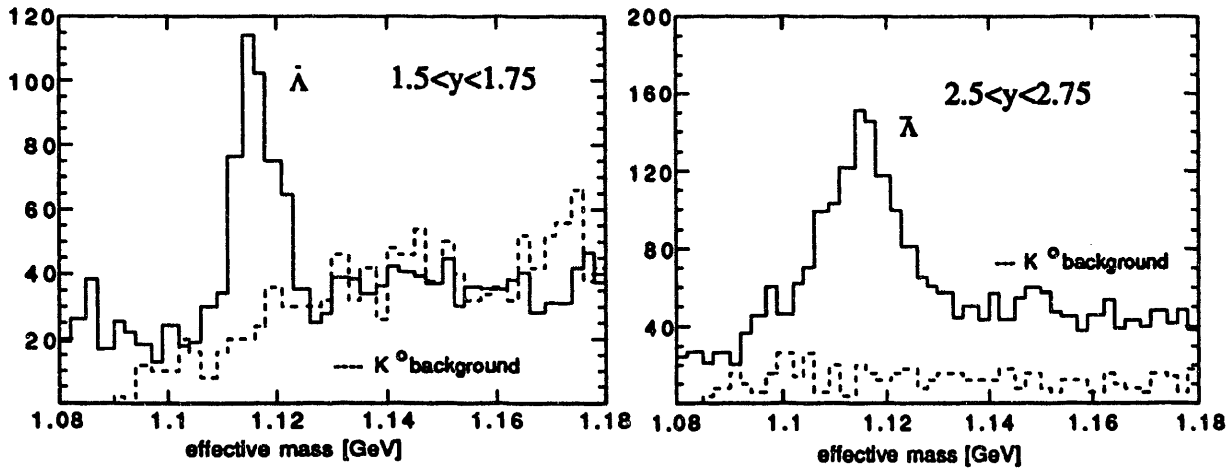


Fig.3. K^0 contribution to the background in the $\bar{\Lambda}$ sample for two selected rapidity bins.

Clear signal and smooth relatively flat background allowed background subtraction by fitting a second order polynomial and integrating the signal above the background. Then the content of each bin was corrected by the appropriately averaged acceptance and efficiency weights.

Since there was no particle identification and Λ and $\bar{\Lambda}$ overlap in certain kinematic area with K^0 it was necessary to make sure that the procedure described above removes the K^0 contamination. In the case of the Λ, the signal was much stronger (Fig. 2) than the possible K^0 contribution but $\bar{\Lambda}$ required a more precise check. Monte Carlo K^0's were generated, embedded into real events, and reconstructed. Statistics for the reconstructed Monte Carlo K^0's as well as their p_t and rapidity distributions were the same as for the data. Then the negative pion was treated as an anti-proton and the effective $\bar{\Lambda}$ mass in the different rapidity intervals was calculated. Fig. 3 shows results superimposed over the $\bar{\Lambda}$ effective mass for the data. It is obvious that the procedure described above removes that background and that the K^0 signal does not contribute to the $\bar{\Lambda}$ peak in any systematic way.

Results.

The first indication of abnormal strangeness production as a function of the event multiplicity in heavy ion collisions was seen by the NA35 experiment[15]. Later WA85 also reported indication of strangeness enhancement for very central events and in a limited phase space[16]. High statistics NA36 data covering the full range of event multiplicities allowed study of that phenomenon with great accuracy. Since the TPC covered only part of the phase space, Monte Carlo simulations were used to correlate the produced multiplicity with the multiplicity measured in the TPC. 2000 Fritiof events were generated and processed by the analysis software. Multiplicity reconstructed in the TPC was compared to the multiplicity generated at the primary vertex. A strong correlation was observed.(Fig. 4).

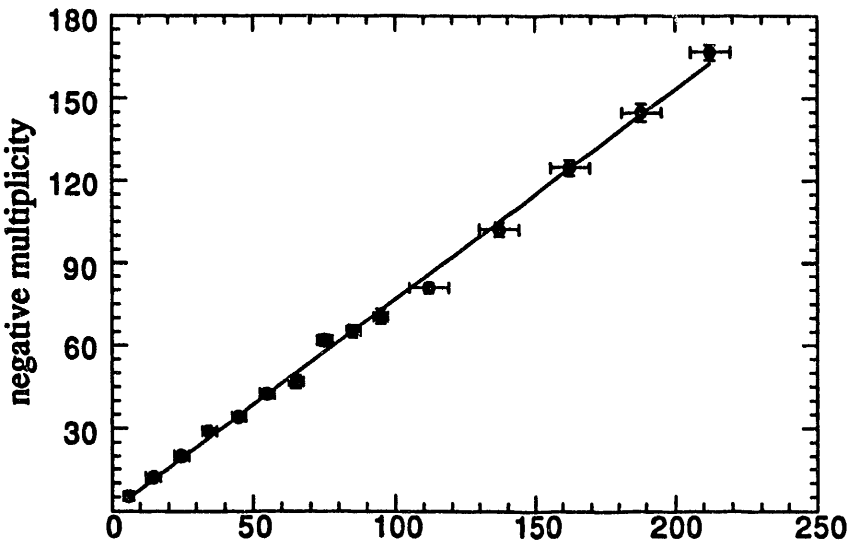


Fig. 4. Correlation between the number of tracks reconstructed in the TPC and number of tracks generated in a primary vertex

A strong signal of gradually increasing strangeness enhancement that saturates at high multiplicities was observed in the S+Pb reaction. Although the initial growth could be compared to the enhancement in p+Pb collisions, the strangeness production per produced negative particle is much higher. We can assume that for the highest multiplicities all the projectile nucleons interacted and scale the multiplicity per participating projectile nucleon. Although such procedure does not take into account the spatial distribution of nucleons in the sulphur nucleus, it allows for a fair comparison between the S+Pb and p+Pb data. Results of such comparison show that the strangeness production in S+Pb is by almost a factor of two higher than in p+Pb (Fig. 5).

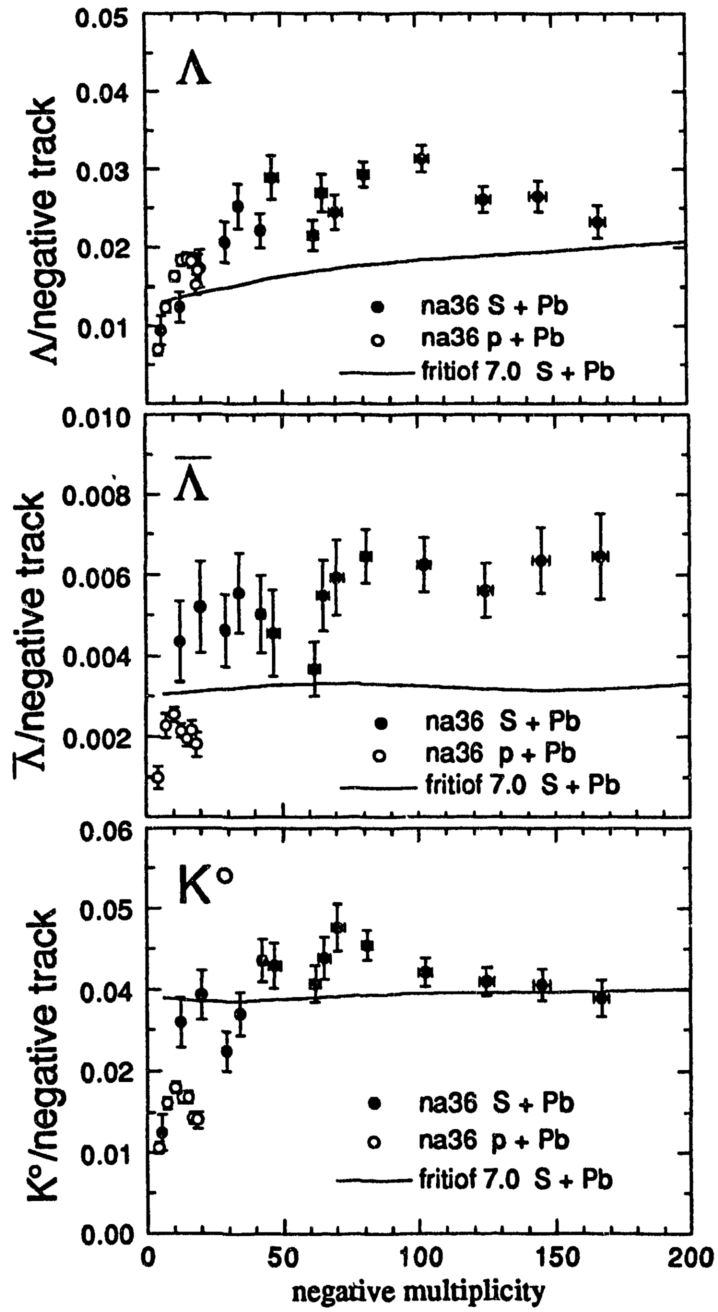


Fig. 5. Strangeness enhancement as a function of multiplicity.

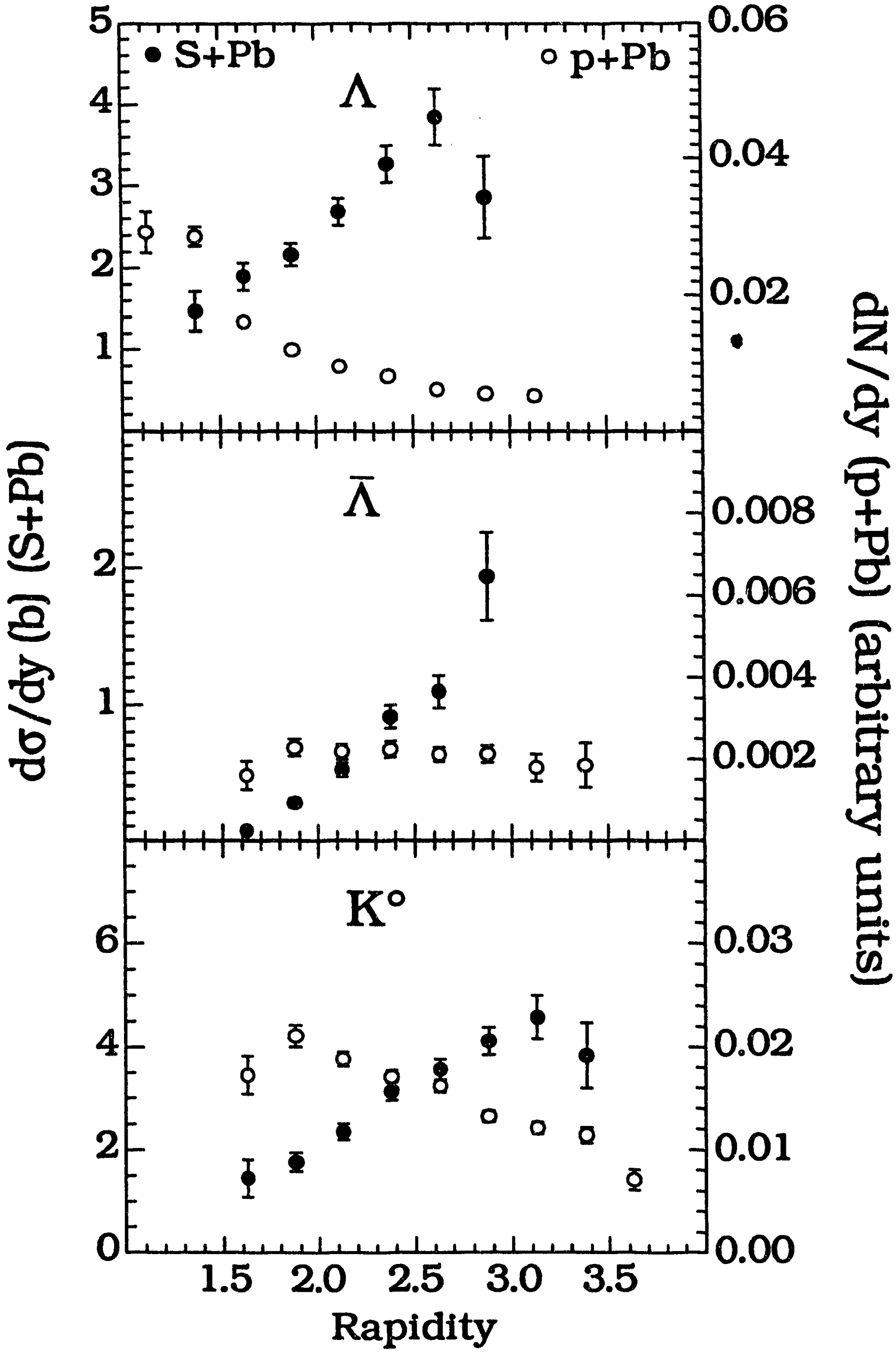


Fig. 6. Rapidity distributions for neutral strange particles.p+Pb results are not normalised and only shapes of the distributions can be compared.

In order to understand the differences between the p+Pb and S+Pb collisions and look for a possible explanation the rapidity distributions were examined. They show that the production mechanisms in case of p+Pb and S+Pb must differ greatly. In the p+Pb case Λ particles are produced in the target rapidity area whereas in the S+Pb reaction a strong source of strangeness is positioned at mid rapidity(Fig. 6).

The ratio of the cross-section integrated above 2.25 units of rapidity and below that value indicates that the peak at mid rapidity gets more pronounced as the multiplicity increases (Fig 7).

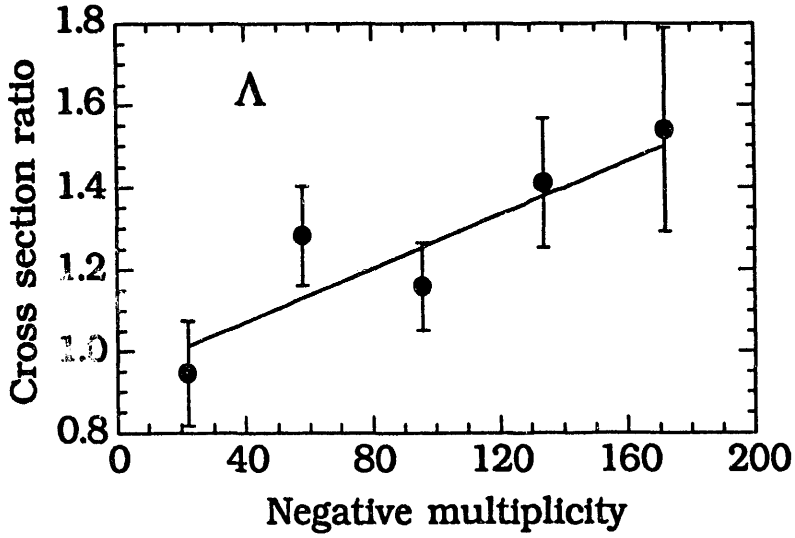


Fig. 7. Cross section ratio $\left(\int_{2.25}^{3.5} \sigma_y dy\right) / \left(\int_{1.25}^{2.25} \sigma_y dy\right)$ as a function of multiplicity.

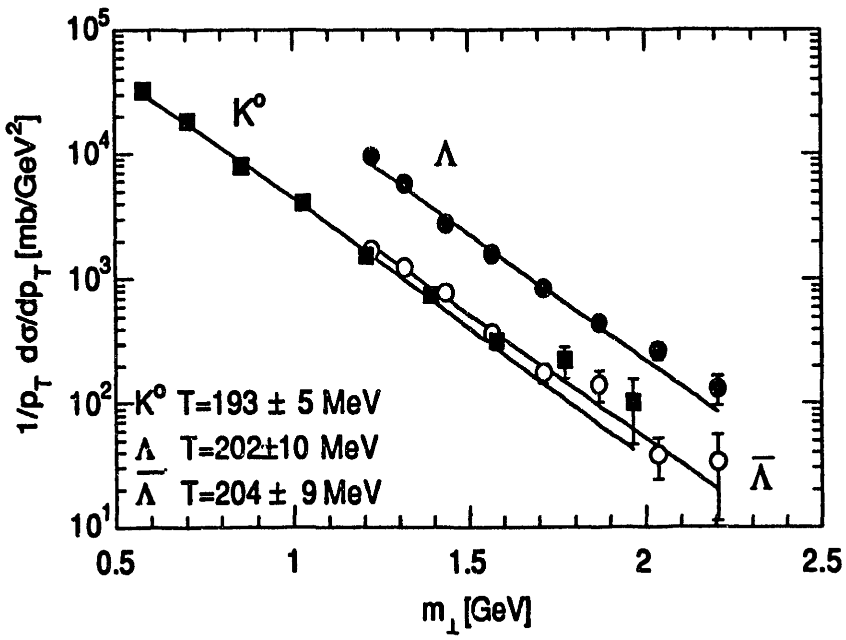


Fig. 8. M_t distributions.

The m_t distributions allow extraction of additional information about the source parameters. Since radial flow modifies mostly the low mass particle spectra, the slope parameter of the Hagedorn[17] formula could be interpreted as a temperature. For all three particle species this parameter comes out ~200 MeV (Fig. 8).

An excess of strangeness production was observed for the first time in p+Xe and p+Ar collisions[18] . It was interpreted as coming from the re-scattering and re-interactions of the produced pions and Λ retention[19]. However, since only the slow particles could interact (Fast particles get out of the nucleus in a time that is shorter than the formation time.), this mechanism enhances strangeness in the target rapidity region only. Since, in the S+Pb collisions the source is positioned at mid rapidity, the production mechanism that enhances strangeness in the ion collisions is clearly different from that for the proton collisions and the heavy ion collisions cannot be interpreted in terms of superposition of proton-nucleus collisions.

J.Rafelski, H. Rafelski and M. Danos suggested that such a shape of the rapidity distributions for the strange particles could be characteristic for an equilibrated fireball decaying at midrapidity. The overall strangeness enhancement as well as the equilibration requirements point towards the QGP nature of that fireball.[20] . The narrower shape of the $\bar{\Lambda}$ rapidity distribution could then be attributed according to J. Ellis to the annihilation of the strange antibarions in the baryon reach target rapidity region.

Another possible explanation offered by W Greiner et all. [21] suggests that the string fusion and formation of color ropes results in a very strong color field that changes the abundance of the strange quarks and results in a similar shape of the rapidity distribution.

Although these interpretations offer different points of view they agree that there is a strong qualitative difference between proton nucleus and nucleus nucleus collisions.

Conclusions

A source of strangeness enhancement at mid rapidity was observed in S+Pb collisions. It becomes more pronounced as the multiplicity of the events increases. The temperature of this source, inferred from the m_t spectra, is approximately 200 MeV. The strangeness production mechanism is clearly different from that in p+Pb reaction. This observation is consistent with a deconfined fireball being formed in the S+Pb collisions but other explanations should be carefully investigated and multistrangeness production studied before any further conclusions can be drawn.

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