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Strangeness Production in Nucleus-Nucleus Collisions: An Experimental Review

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1. INTRODUCTION

In experiments with oxygen (60 and 200 GeV/N) and sulphur(200 GeV/N) ions at CERN-SPS, large energy densities of the order of 2–3 GeV/fm^3 have been observed,[1] which according to QCD calculations,[2] satisfy necessary conditions for the formation of a quark-gluon plasma (QGP) phase. Under such conditions, colour would no longer be confined to hadronic dimensions, and quarks and gluons will propagate freely throughout an extended volume.

Somehow lower energy densities, of the order of 0.7–1 GeV/fm^3, were observed in AGS experiments with 15 GeV/N silicon beams and heavy targets.These energy densities might be adequate for investigations of the pre-equilibrium stage, during which the momentum space distribution has been degradated from its initial value but is not yet thermal.

First experimental results, available now, show promise of seeing signs of a new phase of matter.

Why Strangeness?

According to our standard picture the quark-gluon plasma is characterized both by colour deconfinement and partial restoration of chiral symmetry. Therefore, the production of strange particles is expected to be enhanced by the quark-gluon plasma as compared with thermalized hadronic gas, as has been originally proposed by Rafelski.[3] A recent review with detailed calculations can be found in.[4]

However the main arguments are

- lower energy threshold in plasma,
- increased strangeness density,
- higher production rates due to a shorter time constant,
- enhanced production of antistrange baryons as a consequence of a large ratio of $\bar{s}$ to $\bar{u}$ and $\bar{d}$ quarks in the baryon rich region,
- and, perhaps most importantly, the presence of a large number of gluons in the plasma state.

Furthermore, the information contained in strange particles is expected to be preserved in the evolution of the hadronic matter following the dissociation of QGP.[3,4]

Why Ions?

Central collisions of heavy nuclei are the most-favorable candidates for QGP experiments because of the high energy density in a large interaction volume. The ideal case would be to study central collisions of symmetric systems where there will be no cold nuclear matter (spectators) to complicate interpretation.

In this review the current status of the selective experimental results on strange-particle production, which are relevant to equilibration and QGP formation in nucleus-nucleus collisions, is presented. Figure 1 shows the energy scale ($\sqrt{S}$) of relevant experiments.

Although it is clear that states with very high energy density and high temperatures are

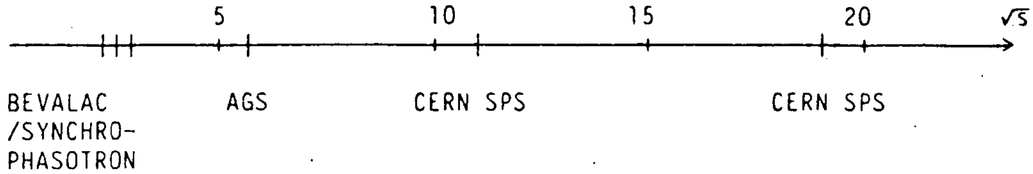

Fig. 1. Energy scale ($\sqrt{s}$) of the heavy ion experiments taking data on strangeness.

formed already in relativistic heavy-ion collisions at CERN and BNL energies, it has not been shown experimentally that equilibrium (neither thermal nor chemical) has been reached. Note that strangeness abundance depends strongly on the degree of equilibrium achieved, either by plasma formation or in hadronic gas. Particle spectra and rates, which will be presented in the next chapters, in principle, should contain needed information: the particle transverse momentum spectrum provides an indication of the temperature, hence the degree of thermal equilibrium, prevailing at various stages of evolution of the collision, whereas particle production rates give insights into the quark content and the amount of chemical equilibrium in the interaction volume.

Table 1 lists BNL and CERN experiments, which have been taking data on strangeness, and their main detectors with relevant acceptances. BNL and CERN results are reviewed in Chapters 3 and 4. Chapter 2 deals with relatively low energy experiments (Bevalac, Dubna, KEK), and Chapter 5 summarizes the current status of experimental findings.

Finally, a few words of caution: Particles carrying strangeness can be produced by several mechanisms and may yield information about properties of the reaction at different times.

Table 1

	BNL 14.5 GeV/N ^{16}O, ^{28}Si		
E802	Magnetic Spect. + TOF	K,π	$P_t \in$ (0.35–1.25) GeV/c $y \in$ (1.2–1.4)
E810	TPC	K°,Λ	$y_\Lambda \in$ (1.2–3) $y_{K°} \in$ (2.2–3)
	CERN 60,200 GeV/N ^{16}O 200 GeV/N ^{32}S		
NA34	Magnetic Spect. + TOF	K, π	$P_t \in$ (0.1–0.6) GeV/c $y \in$ (0.8–1.3)
Na35	Streamer Chamber+ Colo	K°, Λ, $\bar{\Lambda}$,K°,K^+,K^-	$P_t > 0.5$ GeV/c $y \in$ (0.7–3)
Na38	Dimuon Spect.	ϕ	$P_t > 1.3$ GeV/c $y \in$ (2.8–4)
Wa85	Ω Spect. + MWPC + μ-Si	Λ, $\bar{\Lambda}$, Ξ,$\bar{\Xi}$	$P_t > 0.9$ GeV/c $y \in$ (2.3–3)

Therefore, only *systematic comparison* of strangeness production in pp, pA, and AA may allow to disentangle those processes. An additional complication, which affects strange particles less than other species, is related to the fact that observations are made in the final state of the collision, when particles already have hadronized and undergone space-time evolution before reaching detectors.

2. "LOW-ENERGY" EXPERIMENTS

The main emphasis of the "low-energy" nucleus-nucleus experiments at the Bevalac (~2 GeV/N) and Dubna Synchrophasotron (3–4 GeV/N) was not related to QGP formation and degree of equilibration but rather to separation of the nuclear, collective effects from those that may be explained as results of quasi-free nucleon-nucleon collisions. For a review see reference 5 and the references therein. Nevertheless, some puzzling results, clearly relevant to thermalization and/or QGP, were reported. Special attention must be given to the angular distribution (emission angle calculated in the N-N c.m.s.) of Λ's produced in central C–C, C–Ne, and O–Na collisions at 4.5 GeV/c momentum per nucleon, which is *isotropic*. This distribution suggests that the particles were emitted by the thermally equilibrated source. The Boltzmann shape of the kinetic-energy distribution also supports this hyphotesis. Futhermore, the temperatures for Λ's, and π's as well, were found to be very high, ~150 MeV, and in agreement with the values predicted by the thermodynamical model of Hagedorn, calculated under the assumption of full stopping.[6]

This is striking result. The most-natural question, which emerged from these measurements is whether the initial conditions of the collisions (light systems, small volume, low energy density, etc.) are suitable for reaching any kind of equilibrium? This equilibrium is at best transient, because the system is expected to expand and cool before emitting the particles that are observed. The expansion may also be complicated by hydrodynamical flow, etc. How, within such a scenario, can the angular distribution of Λ particles still appear to be so thermal? Perhaps, our scenario is wrong or not accurate enough, or perhaps some other mechanism is responsible for such a spectrum.

Another surprising result was reported from a KEK experiment[7] with $\bar{p}$ on Ta. Since the annihilation of $\bar{p}$ in a nucleus releases ~2 GeV of energy into a relatively small volume, one may expect local heating of nuclear matter ("hot spots") with possible plasma formation and, furthermore, enrichment of strangeness production.[8] And, indeed, enhancement by a factor of 10 in Λ production cross section was found in $\bar{p}$ – Ta collisions at 3 and 4 GeV/N. Various post hoc explanations, based on superposition of hadron-hadron collisions, have been also proposed to avoid the necessity of including plasma formations in conclusions.[9]

3. BNL EXPERIMENTS AT 14.6 GeV/N

Measurements of transverse energy indicate that at 14.6 GeV/N oxygen and silicon nuclei deposit essentially all their energy in central collisions with nuclei heavier then Cu.[10] It therefore seems justified to assess the results of BNL experiments with a simple fireball model in mind.

There are two major experiments measuring strange particle production: E802 and E810.

E810, using TPC detectors, has just begun to collect data; therefore,presented results are still sparse and preliminary.[11] E802, a magnetic spectrometer with time-of-flight wall, however, has been essentially completed, and many results have been already published.[12–14]

Both experiments see an appreciable strangeness signal in 14.6 GeV/N Si–Au central collisions, the largest colliding system available at the AGS. The common results of both experiments are that strange particles have a rather "thermal" shape in the central rapidity region and that the temperature is of the order of 150 MeV with about 10% error.

For more specific information see Fig. 2 and Table 2. Figure 2 shows invariant cross sections for positive (top) and negative (bottom) particles, measured by the E802 experiment, as a function of transverse kinetic energy. The dashed lines show the exponential fits to the data, the solid curves to the Boltzmann distribution. Both lines describe data very well. The inverse slopes T_0 and T_B obtained from these fits for the rapidity interval shown in Fig. 2 are listed in Table 2.

The pion temperature, shown at the top of Table 2, reflects pion freeze-out conditions and therefore is not suitable for probing early stages of the collisions.

A better thermometer of the densest moments in the collision and of the hypothetical

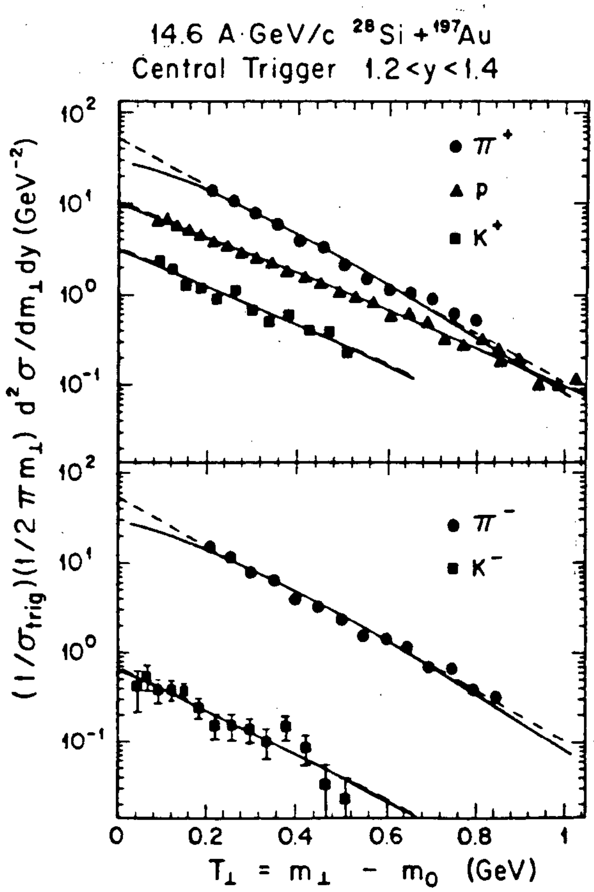

Fig. 2. E802: Invariant cross sections for $\pi^{\pm}$, $K^{\pm}$ and p.

Table 2. E802: Slope parameters and dN/dy for $\pi^{\pm}$, $K^{\pm}$ and proton distributions (Fig. 2) from Si + Au collisions.

	Exponential in $m_\perp$		Boltzmann in $m_\perp$	
Particle	T_0 (MeV)	dN/dy	T_B (MeV)	dN/dy
π^+	162 ± 10	16.0 ± 1.0	126 ± 10	13.8 ± 0.8
π^-	161 ± 10	16.0 ± 1.0	126 ± 10	13.8 ± 0.8
K^+	203 ± 15	2.9 ± 0.2	160 ± 15	2.8 ± 0.2
K^-	175 ± 25	0.53 ± 0.08	140 ± 25	0.52 ± 0.08
p	215 ± 5	16.2 ± 0.3	187 ± 5	16.0 ± 0.3
K^+/π^+		$(18.1 \pm 1.7)\%$		$(20.3 \pm 1.9)\%$
K^-/π^-		$(3.3 \pm 0.5)\%$		$(3.8 \pm 0.6)\%$

QGP phase is the K^+ spectrum, which displays a Boltzmann temperature of $T_{K^+} = 160 \pm 15$ MeV. With this value and the standard perturbative QCD parameters $\beta = 0.109$ GeV/fm^3 and α's = 0.6 one can calculate energy density in the collision,[3] which turns out to be below 1 GeV/fm^3, i.e., just barely in the region where QGP may be possible. Recently reported antiproton multiplicity suppression (1 antiproton per 1000 protons !) in the central rapidity region of these collisions[14] also suggests that BNL conditions are likely to be in the pre-equilibrium, precritical, baryon rich QGP domain.

The K^- temperature is much lower than K^+ due to the large rescattering cross section; the K^-'s freeze out under similar conditions as pions ($T_{K^-} \sim 140 \pm 25$ MeV), so they do not probe early, dense stages of the collisions.

By comparing the integrated spectra one also obtains the particle yield ratios. The observed relative abundance K^+/π^+ or K^-/π^- is obtained by ignoring the possible distortions of the low-energy spectra, i.e., below experimental acceptance ($p_t < 350$ MeV/c). Both K and π spectra are extrapolated to low p_t assuming the Boltzmann or exponential form. For the midrapidity interval $1.2 < y < 1.4$ (the rapidity dependence of T_0 and T_B is discussed in reference 12; reported *variation* of inverse slope with y is as high as 40 MeV!), averaging the similar results given in Table 2 from the two extrapolation methods, the integrated ratios are $(19.2 \pm 3)\%$ for K^+/π^+ and $(3.6 \pm 0.8)\%$ for K^-/π^-. The corresponding ratios in p-p collisions are 4–8 % and 2–5% respectively. Thus, there appears to be significant nuclear effect in the K^+/π^+ ratio. Because of the large uncertainty in K^-/π^- ratio, which is due to the low yield of K^-, one can not determine whether this ratio is different in heavy-ion collisions. The ratio of K^+/π^+ for p-A collisions is intermediate (~12%) between p-p and Si-Au. Theoretically, an enhancement of K^+ is expected if very-high-baryon-density matter is formed (so called "K^+ distillation"[15]). This effect is closely related to associated Λ production. At the hadronic level, the reaction $p+p \rightarrow p+\Lambda+K^+$ has a lower threshold than $p+p \rightarrow p+p+K^+ + K^-$, so associated production is energetically more economical then pair production in high-baryon-density matter. At the quark level, high baryon density implies that the number of u,d quarks greatly exceeds the number of $\bar{u}$,$\bar{d}$. Thus, when a $\bar{s}$ tries to leave the plasma, it has no problem finding a u quark to emerge as a K^+. It is difficult, however, for an s quark to find a $\bar{u}$, but, due to the high abundance of u and d, can form Λ in three-body (u,d,s) process. There result in both scenarios is thus qualitatively the same, more K^+ and more Λ. The precise values of the K^+/π^+ and K^-/π^- ratios do depend on whether the dynamical path entered the plasma phase or not, but details of these processes are still too uncertain to allow for quantitative predictions. So, at this stage the entire observation can be treated *only* as a evidence of the presence of very high baryon densities in the collisions.

The ratio of K^- to K^+, which is, in this rapidity window, about 5.4, reflects essentially only the capability of the K^- to undergo strangeness exchange reactions in the dense baryonic matter.

The second BNL experiment investigating strangeness production, E810, reports results on strange baryons and antibaryons.[11] E810 measured neutral strange-particle production in Si+Au and Si+Cu reactions. The transverse mass lambda spectrum in the central rapidity region has a temperature of about 150 MeV. The K° spectrum, which comes from the forward projectile region and therefore is not directly related to QGP formation, appears to be flatter.

The Λ and K° yields were measured as a function of centrality of the collisions. Figure 3 shows the monotonic rise of the number of midrapidity Λ's per event, corrected for the

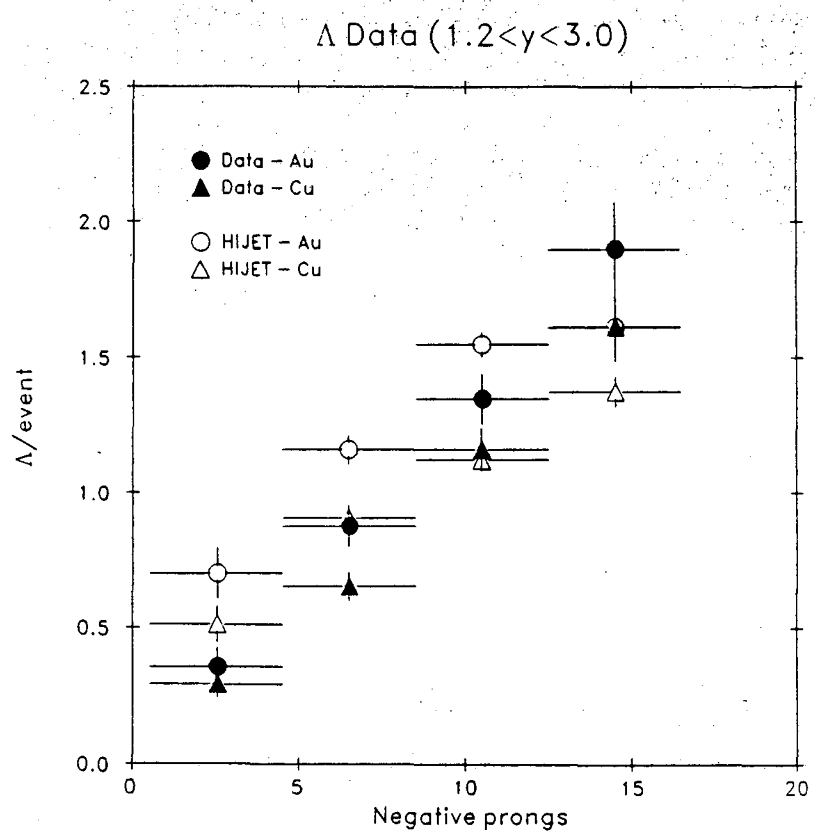

Fig. 3. E810: Λ yield in the rapidity region $1.2 < y < 3.0$ as a function of centrality.

neutral branching ratio, with increasing multiplicity of negative particles, which reflects the dependence on the impact parameter of the reaction. Similar results were observed for forward rapidity K°. E810 does not report an antilambda signal. The original paper[11] says "No detectable $\overline{\Lambda}$ signal is observed." Although it is a very interesting result, it is still preliminary and needs confirmation with the better statistics. Let us imagine, for the moment, the opposite result.Then, given the suppression of antiprotons that is expected for a baryon-rich fireball consisting of either HG or QGP, observation of larger strange antibaryon yields would strongly suggest plasma formation, since without QGP strange antibaryons should hardly be produced at this energy. Therefore, the lack of $\overline{\Lambda}$ signal, assuming that the effect will survive future analysis,should be taken as evidence against QGP formation at AGS energies.

4. CERN EXPERIMENTS AT 200 AND 60 GeV/N

Almost all data at CERN experiments were collected at 200 GeV/N. Given the full stopping, (i.e., all initial energy converted into internal excitation of "fireball") reported at BNL energies, one expects significant degree of nuclear transparency at such a high energy (energy in c.m.s. at 200 GeV/N is 4 times higher then at BNL,Fig. 1). And, indeed, this is the case. Figure 4A shows the rapidity distribution of negative particles produced in central S–S collisions at 200 GeV/N (NA35) as compared with one expected from a fireball with a temperature of 160 MeV (solid line). The experimental spectrum is wider by a factor ~2, which shows that incoming longitudinal energy is not completely thermalized and that a significant fraction of particles continues longitudinal motion. The same holds for baryons. Figure 4B presents the proton rapidity distribution for the same reaction.[16]

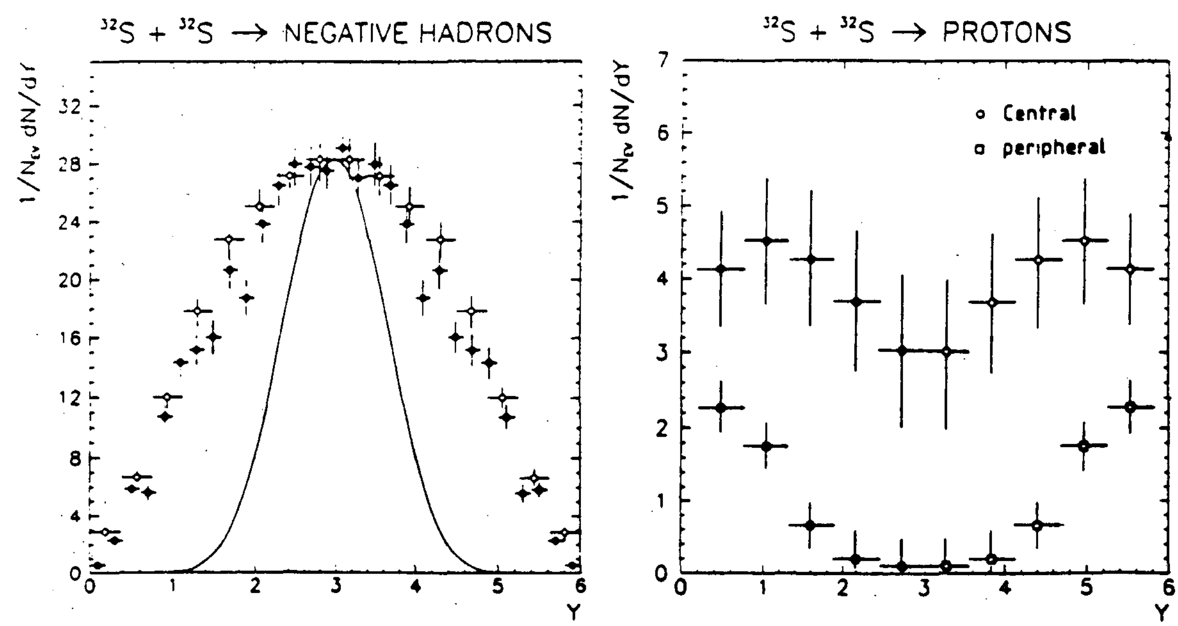

Fig. 4. NA35: Rapidity distribution of A) negative hadrons and B) participating protons in S–S collisions.

Another complication, caused by the high energy, is related to the detection limitations. The rapidity window at BNL is 3.4 units, whereas at CERN at 200 GeV/N it is 6, which in principle, should give less overlap between target, projectile, and interaction rapidity regions. In practice, particles of rapidity 3 in LAB (central rapidity for symmetric systems at CERN) are too fast to be identified in existing detectors. Consequently, at 200 GeV/N experiments cannot identify particles in the most-interesting region, where there is the highest probability of finding traces of the hypothetical plasma phase. The situation looks much better at 60 GeV/N, but almost no data has been taken there.

As shown by Table 2 (Chapter 1), two categories of experiments at CERN have taken data on strange particles: spectrometer experiments (NA34, WA85, NA38) and chamber experiments (NA35, NA36).

Two types of nuclear reactions were studied: symmetric (S–S) and asymmetric (O,S on diverse targets) ones. The particular advantage of the symmetric system, e.g., S–S reactions (NA35 experiment), both in mass and isospin is that the measurement of particles in only one hemisphere of the c.m.s. provides complete information on all nucleons and pions in full phase space. The disadvantage is, no doubt, the presence of significant transparency at 200 GeV per nucleon. In asymmetric reactions, such as the S–W collisions (WA85 experiment), there is the advantage of the much-greater baryon-number stopping. There are difficulties, however, in interpreting the data, which are associated with the overlap of the various kinematic regions and the presence of the cold nuclear spectator matter.

NA34

The External Spectrometer of the NA34 experiment[17] consists of a magnet flanked by two drift chambers and an array of time-of-flight scintillators. The spectrometer views the target only through a very small slit (10 cm high) in a calorimeter wall that drastically limits its acceptance to the target fragmentation region ($0.8 < y < 1.3$), which is not of direct relevance to the issue of QGP.

Figure 5A shows the K/π^+ ratio for positive and negative particles as a function of p_t in S–W collisions.[18] The inner error bars indicate statistical errors, the outer error bars statistical and systematical errors combined. The dotted lines represent the K/π ratio from p–p data scaled to the proper y–p_t interval. A clear excess in the ratio of positives is seen over that expected from p–p. No such excess is present for the ratio of negatives in the p_t interval under study. In Fig. 5B the K/π ratios for 200 GeV p–W are plotted as a function of p_t. Similar trends are observed as in the S–W data (Fig. 5A), but with larger statistical errors.

The observed excess of K^+/π^+ is similar to one reported by the E802 collaboration, although the bombarding energies differ by more than an order of magnitude and acceptances are quite different. Given the acceptance range of the NA34 apparatus and the magnitude of the K/π^+ ratio in the target fragmentation region ($y < 1.3$), where scattering on cold nuclear matter is dominant, one expects much stronger enhancement in midrapidity. This must, presently, be regarded as a speculation only.

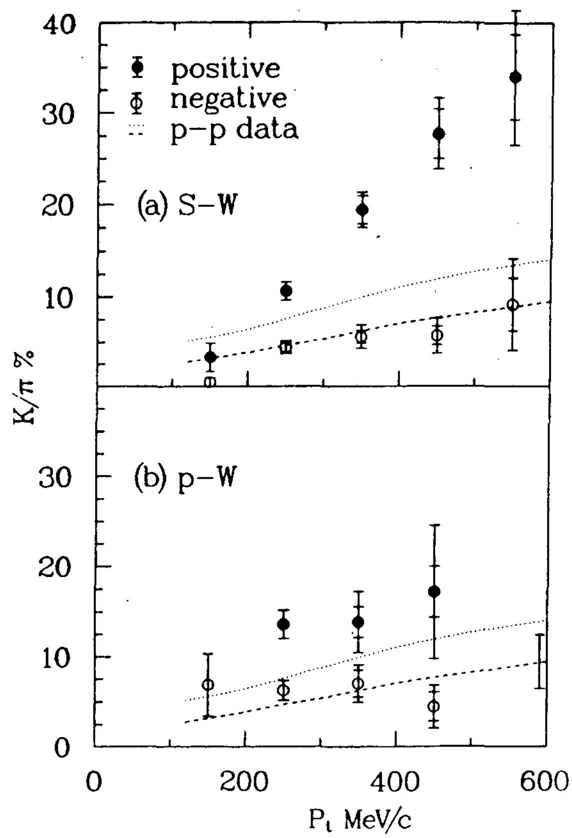

Fig. 5. NA39: K/π ratio for positive and negative particles as a function of p_t a) in S-W and B) in p-W collisions.

NA35

The NA35 experiment studied 60 and 200 GeV/N p and O beams and 200 GeV/N S beams incident on nuclear targets varying in mass from S to Au.

The large volume Streamer Chamber, main detector of the NA35 experiment, permits measurement of Λ, $\overline{\Lambda}$, and K° with the efficiency on the order of 10% via their $p\pi^-$, $\bar{p}\pi^+$, and $\pi^+\pi^-$ decays, respectively, and of K^+ and K^- via their $\mu\nu$, 2π and 3π decays.

In O–Au and p–Au reactions at 60 and 200 GeV/N, investigation of the quark gluon plasma production is hampered by inadequate predictions of production via hadronic processes. Extraction of model independent quantities such as particle yield ratios is very difficult because the experimental acceptances in (p_t,y) are neither complete nor identical for various particles. Results on O–Au and p–Au will not be discussed here since they are not directly related (acceptance covers backward of mid-rapidity region of phase space only) to the discussed issue of QGP. However, particle yields and spectra, in limited acceptance, as well as detailed information on the procedure can be found.[19]

In S–S collisions[20] it suffices to measure particle production in the backward hemisphere of the c.m.s. because of the symmetry of the reaction. The acceptance of the experiments is then large enough to allow an extrapolation of particle production rates to full 4π phase space. Figure 6A,B and C show the ratios of the average number of Λ, $\overline{\Lambda}$, and K° to the total number

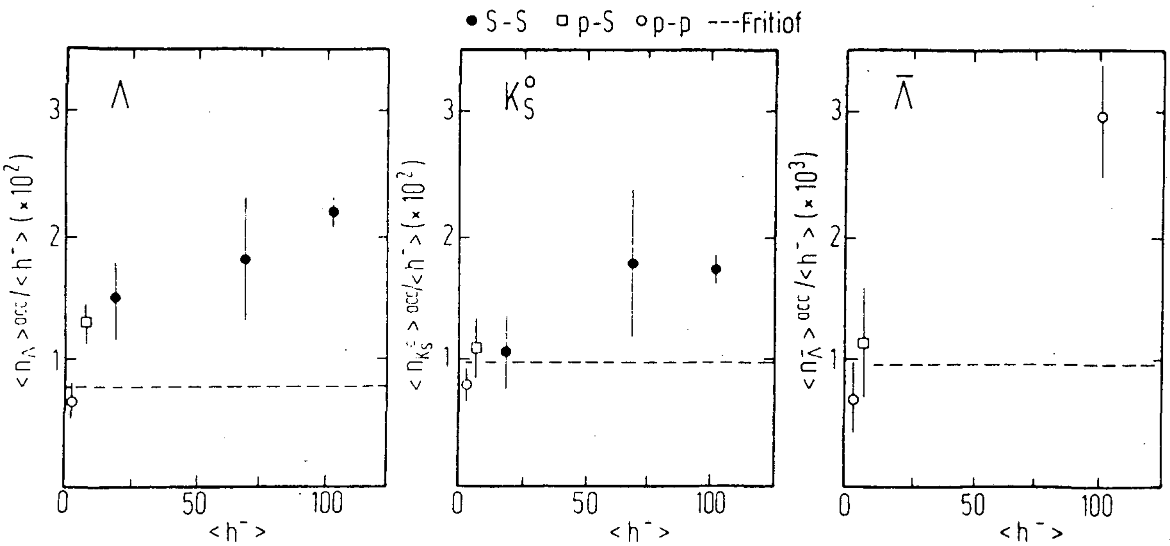

Fig. 6. NA35: Ratio of the mean multiplicities <Λ>, <K°>, <Λ̄> observed in NA35 acceptance to the total negative hadron multiplicity <h⁻> in S+S collisions.

of observed negative particles (mainly pions) produced in the S–S collision at 200 GeV/N as a function of the event multiplicity.

The three points plotted in each figure represent peripheral, intermediate, and central collisions respectively. The Λ/π, $\bar{\Lambda}/\pi$ and K°/π ratios increase linearly with multiplicity and reach 2–3 times the values expected from nucleon-nucleon collisions (dashed lines on Fig. 6A, B and C represent Fritiof calculations). Note that other features of the same collisions are in very good agreement with Fritiof predictions.[21] Furthermore, the distribution in S–S collisions is *flat* in the interval $1.5 < y < 4.5$ and, in particular, is present in the central rapidity region, which is believed to be almost baryon-free since the numbers of positive and negative particles (mainly pions) are nearly equal. So, one would expect few, if any Λ's there unless ". . . a QGP fireball had been formed . . .".[4]

The next very important question is, where did the $\bar{\Lambda}$'s whose ratio grows with the event multiplicity as fast as in the and K° case, come from? Figure 7 shows the rapidity distribution of $\bar{\Lambda}$ with the maximum observed in the central rapidity region. So, Λ and $\bar{\Lambda}$ are produced "together" (i.e., in the same rapidity region), which makes the argument in favor of QGP formation much stronger.

Table 3 gives a comparison of negative and strange particle production per event in 4π in p–p and S–S collisions at 200 GeV/N. One sees that the yield of $\bar{\Lambda}$ in S–S is *1.5 per event* (!), which is about 115 times higher than in p–p collisions. This enhancement has to be confronted with the 36-fold enhancement of the negatively charged tracks.

This is the most *striking* result of all the current experiments in the field of QGP. There is no explanation for such a result with any type of cascading in the hadronic gas. There is simply no imaginable process that could produce such an number of $\bar{s}$ quarks within any hadronic fireball scenario.

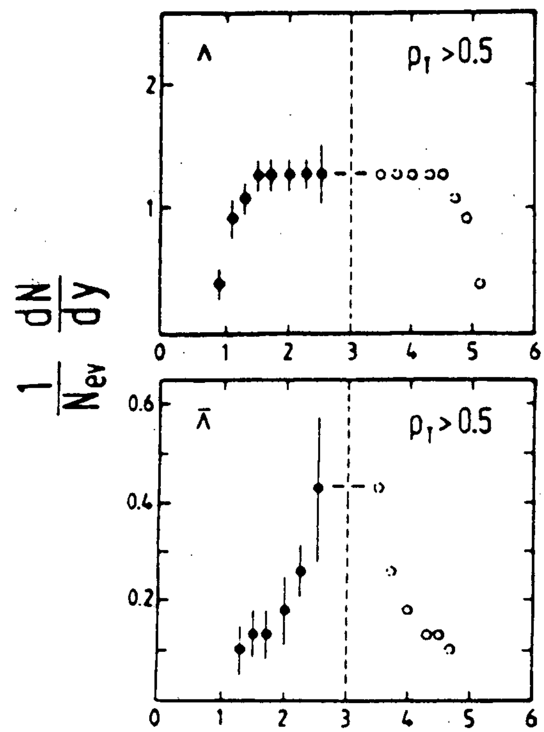

Fig. 7. NA35: Rapidity distribution for Λ and $\bar{\Lambda}$ in central S–S collisions.

Table 3

<h–>	2.85 ± 0.04	~36× ⟶	103 ± 5
<$\bar{\Lambda}$>	0.013 ± 0.004	~115×! ⟶	1.5 ± 0.4
<Λ>	0.095 ± 0.01	~86× ⟶	8.2 ± 0.9
<K°>	0.17 ± 0.01	~62× ⟶	10.7 ± 2

Also, the strangeness flavor production is, consistently, up by the same factor ~2.5 in the K/π ratio in the same reaction in midrapidity, (y = 3), which is 0.15, compared with 0.06 for a p-p system of similar energy.

NA36

The NA36, TPC experiment, designed primarily to investigate strange particle production, has yet to deliver physics results.

WA85

Due to some interpretational ambiguities of the total strangeness content in QGP and HG, mainly related to our present ignorance of the reaction dynamics, *strangeness density*, which is, no doubt, higher in QGP then in HG[2,22] became the primary observable to be determined experimentally. This quantity is indirectly accessible to measurement in the form of multistrange baryon abundances, i.e., cascades and omegas.

For the first time, production of Ξ^- and $\bar{\Xi}^-$ has been observed by the WA85 experiment in S–W and p–W interactions at 200 GeV/N. The WA85 set-up, with its Ω Spectrometer and MWPCs, is designed to allow the central rapidity ($2.2 < y < 3.2$), high p_t ($p_t > 1$ GeV/c for V°) region to be studied at high rates.[23] Several tracks are recorded out of several hundred produced in a central collision, making reconstruction of both strange an multistrange baryons possible in this kinematic region. The two silicon microstrip detectors near the target measure the charged particle multiplicity in the pseudorapidity range $2.1 < \eta < 3.4$, which provides information on event centrality.

Figures 8A,B show invariant mass plots for cascades and anticascades, which are identified by the $\Lambda\pi^-$ and $\bar{\Lambda}\pi^+$ decays pointing to the secondary vertex. The preliminary ratio $\bar{\Xi}^-/\Xi^-$ = 0.43 ± 0.07 for S–W, and 0.027 ± 0.06 for p–W was obtained in the kinematic region $p_t > 1.0$ GeV/c, $2.1 < y < 2.9$. Quoted errors, statistical only, are estimated to increase by about one sigma when efficiency and geometrical acceptance corrections are taken into account.

Clearly more statistics are needed to confirm this remarkably *large* enhancement in the anticascade-to-cascade ratio in S-W collisions as compared with p-W. Also, it is important to know by how much the $\bar{\Xi}^-/\bar{\Lambda}$ ratio is enhanced in S-W reaction compared with the p-W reaction. Due to complexity of required corrections, this ratio is not available yet. Analysis, however, is in progress.

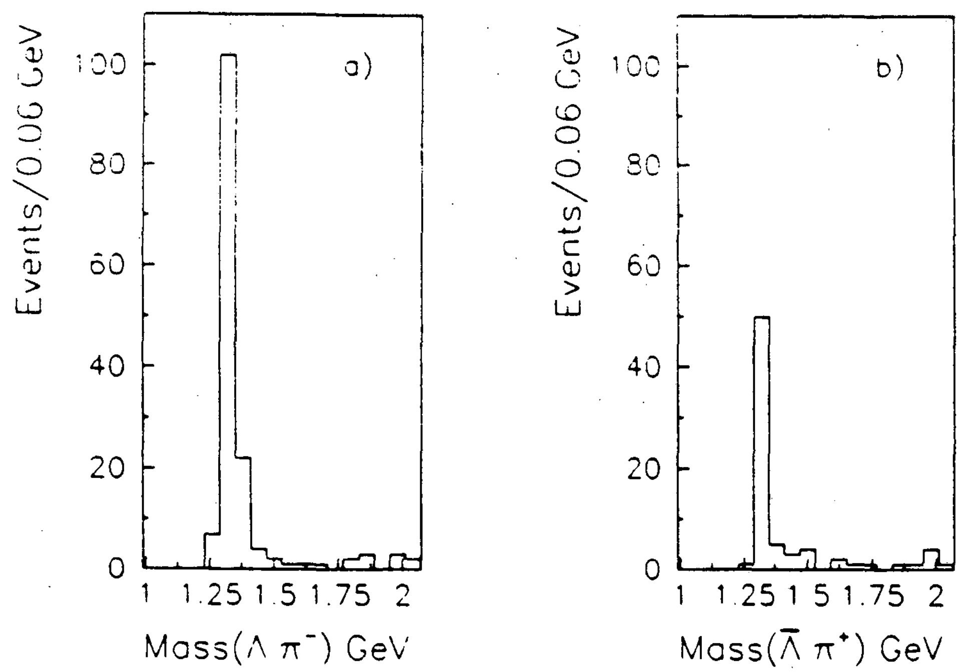

Fig. 8. WA85: Effective mass distributions for cascades and anticascades as (a) $\Lambda\pi^-$ and (b) $\bar{\Lambda}\pi^+$, respectively.

Referring back to the results on singly strange particles, the following was reported:

The yield of both Λ and $\bar{\Lambda}$ per negative track in the central rapidity region is enhanced by a factor of 1.7 compared with the p-W data.

The ratio of $<\bar{\Lambda}>/<\Lambda>$ in the same acceptance is 0.24 ± 0.8. For comparison, the same ratio from the NA35 experiment, restricted to WA85 acceptance, is 0.29 ± 0.10. Agreement, within error bars, is very good.

The preliminary results on the ratio of negative particles, Λ and $\bar{\Lambda}$, to the charged-particle multiplicity measured in the silicon detectors are plotted on Fig. 9. The ratio for Λ and $\bar{\Lambda}$ remain approximately constant for multiplicities above 40, which corresponds to very central collisions.

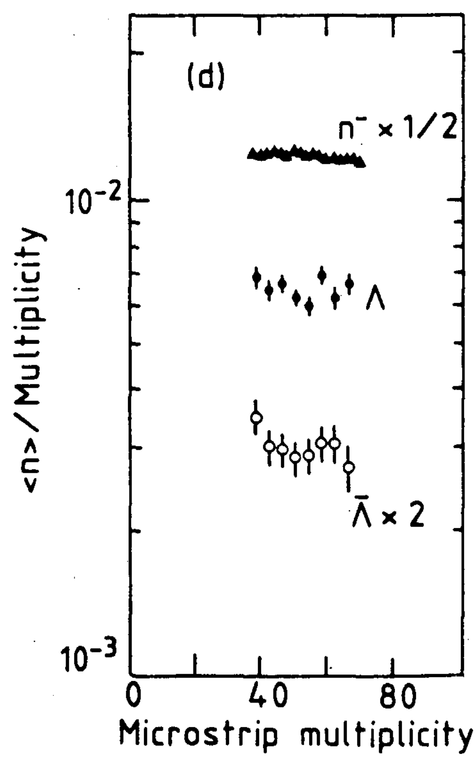

Fig. 9. WA85: Ratios of negative particles n–, Λ, $\bar{\Lambda}$ to the number of charged particles detected in the silicon microstrip detector vs the latter number.

NA38

The NA38 experiment, which consist of a dimuon spectrometer and electromagnetic calorimeter, measured mass and p_t spectra of dimuons produced in 200 GeV/N p–U, O–U, and S–U reactions, in correlation with the neutral transverse energy E_t of the collision.[24]

To reduce combinatorial background from kaon and pion decay muons in the μ-pair spectrum, p_t and p_l cuts were imposed, which reduced available phase space to $p_t^{\mu\mu} > 1.3$ GeV/c and $2.8 < y < 4$. Measured $\mu^+\mu^-$ mass spectra (Fig. 10) in p–U, O–U, and S–U at 200 GeV/N show evidence for φ, ρ, and ω vector mesons.[25] The clear double-peak structure, seen in the muon-pair mass region of 0.6–1.2 GeV, becomes more pronounced with increasing

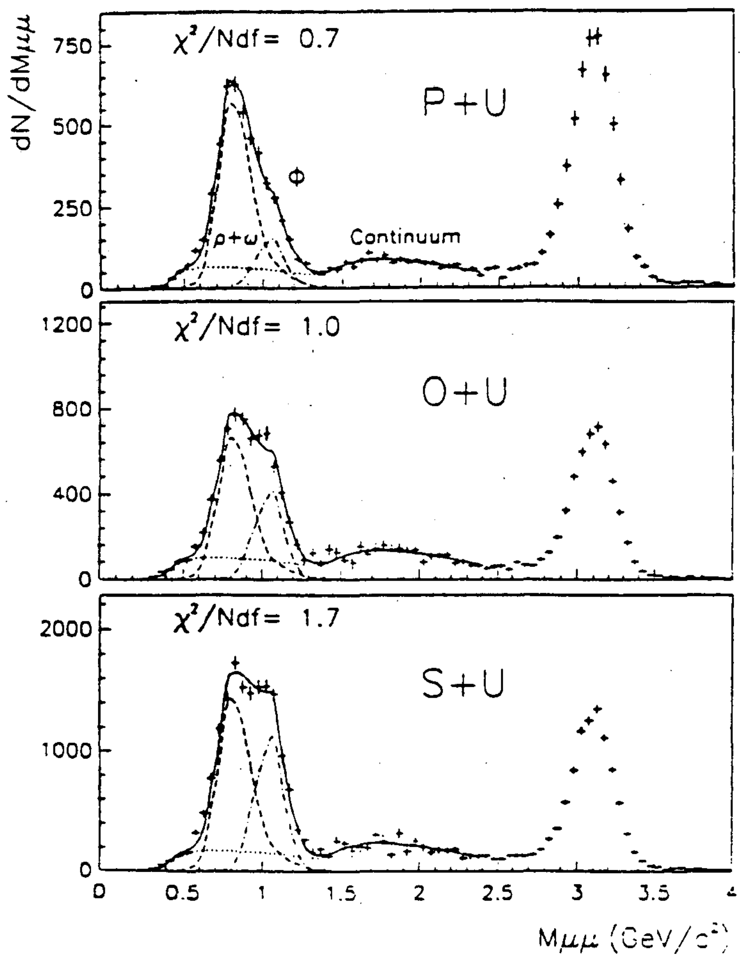

Fig. 10. NA38: Dimuon mass spectra in P–U, O–U and S–U collisions.

mass of the colliding system. By fitting $\mu^+\mu^-$ mass spectra (solid lines on Fig. 10) under the assumption of an equal-production cross section for ω and ρ, a ϕ/(ω+ρ) ratio is extracted and reaches the very high value of 0.59 ± 0.02 in S–U collisions.

The ratio ϕ/(ω+ρ) versus $E_t \times A^{-2/3}$ in O–U and S–U collisions, normalized to the result for average p–U reactions, is shown in Fig. 11. One observes that it rises with energy density (which is $\sim E_t \times A^{-2/3}$) to 3 times the p–U value and scales, also, with the energy density.

This new observation parallels the one by the NA35 Collaboration in S–S collisions, where enhancement of the ratios of kaons, Λ's, and $\bar{\Lambda}$'s over the total multiplicity as a function of centrality of the collision, was seen. Both findings point towards enhanced strangeness production in central A–A collisions.

An enhancement of the hidden-strangeness ϕ-meson production in nucleus-nucleus collisions compared with its value in p–p has been already predicted earlier[26] as a possible signal for QGP formation.

However, a qualitative description of the trend of the data was recently obtained[27] by solving the rate equations for ϕ-production and -absorption via secondary collisions in the dense reaction zone (solid lines in Fig. 11).

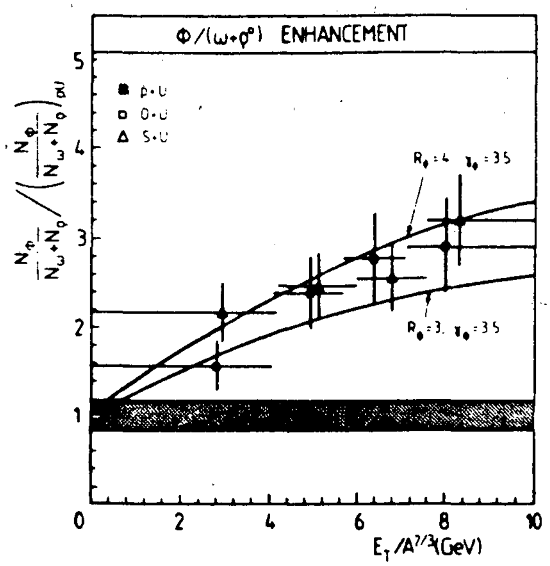

Fig. 11. NA38: $\phi/(\omega+\rho)$ ratio as a function of transverse energy from O–U and S–U collisions, normalized to the ratio measured in p–U events.

Another explanation, based on the substantial increase of ϕ production cross section due to the K + K $\rightarrow \phi+\rho$ and K + Λ $\rightarrow \phi$ + N processes was also successful in fitting the data.[28] Authors of both reference 27 and reference 28 do not see, presently, any reasons to invoke additional, nonhadronic mechanisms to explain of reported ϕ enhancement. Of course, the observation of a stronger effect in the reactions with heavier systems in future experiments or demonstration that the effect exists in the full phase space will require a revision of the hadronic rescattering scenario, while still being consistent with the QGP hypothesis.

At the end, word of caution:

The $\phi/(\omega+\rho)$ ratio is so small in p–p collisions (~1/40) that even very tiny additional contribution from rescattering can lead to an observable enhancement of about 3. However, it will be very difficult to explain enhancement higher then 4 via such a processes. [27]

m_t SPECTRA

Though strangeness abundance (especially singly strange particle abundance)may not be an unambiguous signal, the spectra of strange particles carry more additional and detailed information. At this moment only Λ, $\overline{\Lambda}$, K^+, K^-, and K° are available, but analysis of Ξ^-, $\overline{\Xi}^-$, and ϕ is in progress. Since rapidity plots for Λ's and $\overline{\Lambda}$'s have been shown already (Fig. 7), here, only m_t distributions will be discussed in details.

At the simplest level, m_t scaling ($m_t = \sqrt{p_t^2 + m_o^2}$) should hold in purely thermal models, reflecting the temperature at which particles are radiated. M_t scaling implies that on a plot of the invariant cross section (in logarithmic scale) versus m_t, points for particles of different masses fall on a universal curve, or, in a more limited definition, points for particles of different masses fall on lines characterized by universal slope. Indeed, transverse mass spectra in O–Au collisions (NA35 data in the acceptance restricted to the backward hemisphere of phase space), at both energies, 60 and 200 GeV, are reproduced well by a thermal model, with a single slope parameter of the order of 190–210 MeV.[18] Figure 12 shows the m_t spectrum for pions, kaons, and lambdas for O–Au at 60 GeV (straight lines are drawn to guide the eye). Even more pronounced is the situation in the S–S[19] collisions in which a common temperature of 193–194 MeV is recorded for Λ, $\overline{\Lambda}$, and K° (Fig. 13); the p–S results have a much-lower temperature for Λ (174 MeV) and a higher one for K° (206 MeV) indicating a different reaction mechanism. In the heavier system, e.g., S–W (WA85), the temperatures of negatives Λ and $\overline{\Lambda}$ is higher than the temperature in S–S, and equals 227 MeV. The K^+

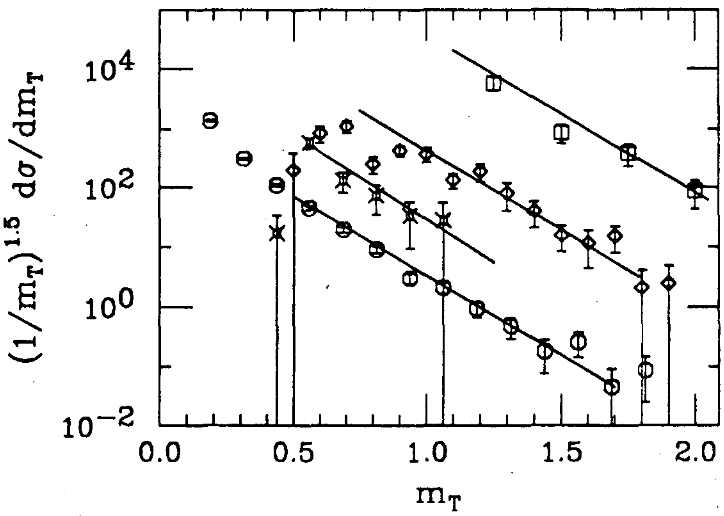

Fig. 12. NA35: Transverse kinetic energy spectra of π, K±, K° and Λ, in O–Au collisions of 60 GeV/N.

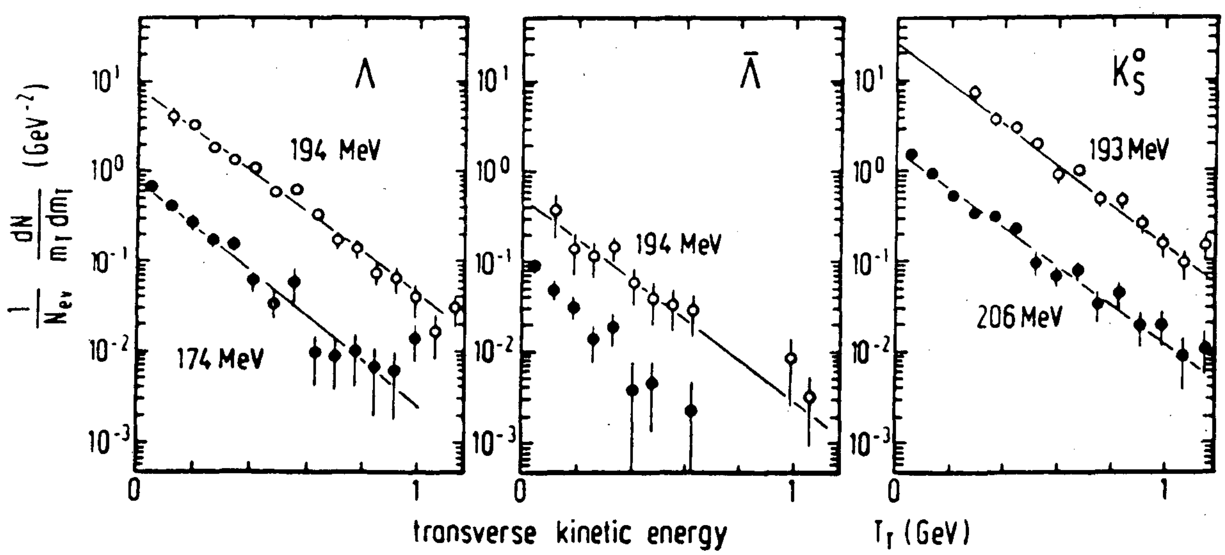

Fig. 13. NA35: Transverse kinetic energy spectra in central S–S (upper) and p–S (lower) collisions.

temperature, reported by NA34, is of the same value, namely 223 MeV, only K^- are significantly lower, about 100 MeV, probably due to their high cross section for interactions in a non-baryon-free environment.

So, in all CERN experiments, high temperatures, similar for different species, were attained. Agreement with the postulated thermal model is remarkably good.

There are, of course, several processes affecting such a simple picture, which have been already discussed briefly in Chapter 3.

5. CONCLUSIONS

It has been reported that the temperature and energy density suitable for pre-QGP (BNL) and QGP (CERN) conditions have been reached in the heavy-ion collisions.[1] This is *not* a surprise, since that was the initial motivation for designing these experiments. However, observation of signatures of the produced plasma would be a surprise, since the size of the interaction volume for light projectiles (as O or S) seems *too small* for equilibrium to be established.[3]

Bearing this in mind one should look at the experimental results. The most striking signal of something unusual happening in the CERN heavy-ion program was observation, made by NA35, of a substantial enhancement of neutral-strange-particle production in central S–S collisions. There are many more antilambdas than expected from particle cascades or any other conventional processes. Anomalously large Ξ^- and $\overline{\Xi}^-$ multiplicities in S–W reactions have been found by the WA85 collaboration. Clearly, multistrange baryons and antibaryons are expected to provide crucial information, since they are predominantly formed in the regions of very high strangeness density. Unfortunately, data on $\overline{p}$, $\overline{\Lambda}$ and $\overline{\Xi}^-$ production rates (in the same phase space windows !), essential for final conclusions, are not yet available. Also, hidden strangeness, ϕ meson, enhancement in O–U and S–U collisions relative to p–U and p–p (NA38), and K^+/π^+ excess in S–W (NA34) at the same energy support intriguing effects reported by NA35 and WA85 experiments. Enhancement in the K^+/π^+ ratio in central Si–Au reactions was also reported by the E802 experiment at a much-lower energy, 14.6 GeV/N.

Although the presented results on strange-particle-abundance anomalies agree well with earlier predictions about the QGP response, they do not yet constitute convincing evidence for deconfinement. There are, presently, only a few points known in the parameter space, so it is conceivable that an *alternate* interpretation of the data will be found.

More accurate and detailed data are needed to determine crucial parameters of models and calculations.

Further runs of present experiments are planned at available accelerators at BNL (AGS 14.6 GeV/N) and at CERN (SPS at 60 and 200 GeV/N, in particular the lower end of the energy range) with improved equipment. One hopes that analysis of 60 GeV/N S–S collisions will take place next year and will fill the present gap between the 14.6 GeV/N BNL and 200 GeV/N CERN energy domains, providing information on the early, very hot and compressed stage of the collisions without complications caused by nuclear transparency. In the near future, probably 1993, the SPS program at CERN will be extended to much-heavier projectiles such as Pb at 170 GeV/N, which would provide an opportunity to study collisions with much-larger initial volume. And, of course, RHIC will open a new energy domain with a further increase in energy density and a nearly baryon-free central collision region.

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