The Role of Hyperons in Relativistic Heavy Ion Collisions

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In the last two decades nuclear physicists were trying to discover a new phase of nuclear matter called the Quark Gluon Plasma (QGP). This plasma state was predicted as one of the transient phases during the de-excitation of the cosmological big bang. It is assumed that a reenactment of these initial conditions is possible through the collision of two highly relativistic heavy ions. The generated plasma phase will correspond to a short lived and highly excited state of matter, which will convert back into a conventional hadron gas after less than 10^{-21} sec, but the composition of the particle emission spectrum from the produced fireball is expected to have ramifications for cosmology and the standard model. Measurements that were proposed as signatures for this phase transition were obtained in heavy ion collisions at the Bevalac (LBL), AGS (BNL), and SPS (CERN) accelerators. No unambiguous evidence for the QGP formation has yet been found, though. With the advent of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), heavy ion physics will enter a new energy regime and the question is whether the originally proposed signatures are still sensible and detectable at these higher incident energies. In particular measurements related to hyperon formation were advocated as potential signatures and were tested in numerous fixed target experiments at the AGS and the SPS. In this article I will first review the existing set of hyperon measurements and then extend the scope of hyperon physics to the RHIC energy regime.

1. Introduction

Since the beginning of Relativistic Heavy Ion Collisions at the BEVALAC, the quest for evidence of a phase transition between hadronic matter and a chirally symmetric and deconfined phase, called the Quark Gluon Plasma, has led to numerous proposed hadronic and leptonic signatures. In the hadronic sector the properties of hyperon production are of particular interest. Suggested measurements relating to hyperon properties are numerous and span from simple hyperon yields (as evidence for strangeness enhancement), over hyperon-antihyperon ratios (as evidence for strangeness equilibration) to strange quark matter formation.

The main condition for a successful measurement of hyperons in heavy ion collisions is the proper reconstruction of a secondary vertex in an environment that is dominated by pion, kaon, and proton emission. In a standard central Au-Au collision at RHIC around 10,000 charged particles are produced of which around 2,500 are within the acceptance of a standard collider detector with 2π azimuthal and full radial coverage. Only about 2% of those particles originate from hyperon decays. By adopting high resolution position detector concepts (e.g. the RHIC-STAR detector is relying on a Silicon Vertex Tracker and Time Projection Chamber combination) and track reconstruction techniques that were successfully applied in high energy physics to measure charm, bottom and ultimately top quark physics, the Relativistic Heavy Ion community was successful in measuring hyperon production with good efficiency and excellent resolution. Kinematic properties allow further to distinguish between a variety of neutral strange particles. Fig.1 shows a so-called Armenteros plot based on the statistics obtained in around 1000 simulated central Au-Au collisions at RHIC energies.

By plotting the fractional difference of the daughter momenta (α) on the x-axis and the momentum component of the positive decay product transverse to the parent trajectory (p_T) on the y-axis a clear separation of the neutral strange mesons (K_s^0 have a symmetric decay and form a large arc around α=0) from the hyperons (Λ,$\overline{\Lambda}$ have asymmetric decays and form small arcs away from α=0) is apparent. The techniques also aid in measuring an almost background free sample of multiply strange baryons. Besides the measurements of Λ, Ξ^-, Ω^- and their respective anti-particles, we also attempted the discovery of more exotic hyperon related objects, like the H-dibaryon and strangelets, which should form

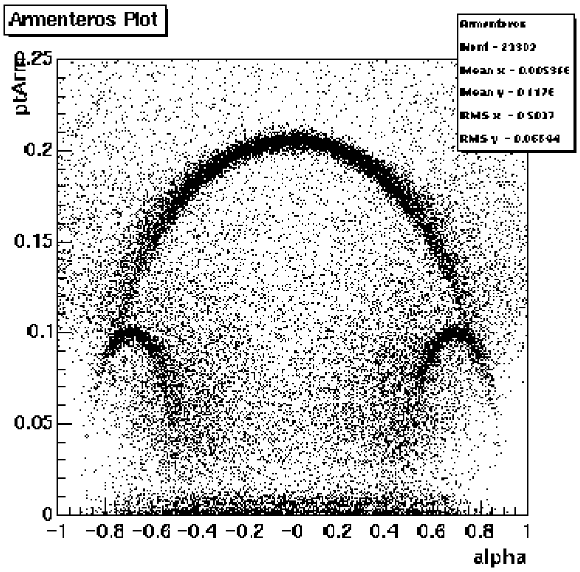

Figure 1. Typical Armenteros plot for strange particles (K_s^0, Λ, and $\overline{\Lambda}$) for 1000 central Au-Au events at RHIC energies.

when the hyperon density in a part of phase space exceeds a critical value. Heavy ion reactions are considered an ideal environment for hyperon clustering, simply because the high density, low temperature environment favors a coalescence type interaction. In this sense the lower energy fixed target experiments, which typically generate very high particle density in the central fireball region are more suitable for strangelet formation than the very high energy collider collisions in which the beam nuclei are considered to be transparent. Here the central particle density is small but the temperature is high, which will lead to high escape velocities for produced hyperons. Thus, the coalescence probability is low.

In the following I will give a detailed review of the present status of measurements in those key sectors after two decades of fixed target experiments and then relate this information to future measurements made possible by the new Relativistic Heavy Ion Collider (RHIC) at BNL.

2. Past Hyperon Measurements in AGS and SPS fixed target experiments

The main motivation for hyperon measurements in relativistic heavy ion collisions goes back to the prediction that strange quark production will be strongly enhanced and chemically equilibrated in the case of a QGP formation [1]. Fig.2, taken from [1], summarizes the predictions for the simple measurement of anti-hyperon over hyperon ratios in the case of a hadron gas model (HG) and a Quark Gluon Plasma model (QGP).

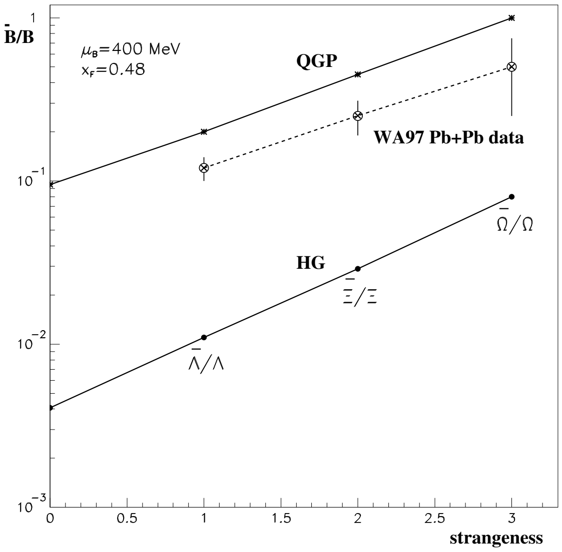

Figure 2. Theoretical Predictions for the Anti-Baryon over Baryon ratios in the case of a Hadron Gas (HG) and a Quark-Gluon Plasma (QGP) under Certain assumptions (fixed μ_B and x_F). Predictions are based on [1], data are taken from [3].

Certain assumptions, in particular the magnitude of the baryochemical potential (μ_B) will modify these calculations slightly, but the signature is preserved as long as thermal equilibration can be assumed. The main argument in this theory is that in a QGP the $s\bar{s}$-pair formation is dominated by the early partonic interaction, specifically gluon-gluon processes, which strongly enhance strangeness production [2] compared to simple rescattering processes that are required in a hadron gas to generate hyperons and anti-hyperons. In addition, the hard processes as described by QCD generate as many s-quarks as $\bar{s}$-quarks. Thus strangeness will equilibrate as predicted for the $\Omega/\overline{\Omega}$-ratio in a QGP (see Fig.2). In a hadron gas the processes generating the hyperon are always favored over the anti-hyperon production, simply because the remnant light quark multiplicity leads to matter rather than anti-matter production.

High statistics measurements, in particular at the CERN SPS accelerator, where the incident energy is sufficiently large to produce measurable quantities of multiply strange hyperons, have led to strong indications that hyperon production is indeed enhanced and maybe even equilibrated. Fig.3 shows the latest strangeness enhancement factors, as measured by CERN experiment WA97 [3], by comparing the actual measured abundances in nucleus-nucleus collisions at 160 GeV per nucleon to scaled-up abundances from proton-nucleus collisions at the same incident energy. The scaling assumes that a nucleus-nucleus collision is simply a superposition of single proton-proton collisions. Agreement with the superposition model would indicate that a nucleus in a collision at relativistic energies behaves like a collection of independent nucleons, whereas any deviation from this model indicates collective behavior of the nucleus, which is widely considered a pre-requisite for a thermally equilibrated system. A phase transition will require thermalization of a finite size volume of hadrons. Fig.3 seems to indicate evidence for such a collective behavior of the fireball generated in a nucleus-nucleus collision. Obviously the enhancement is statistically significant and seems to rise as a function of strangeness content.

The most recent ratios, measured with the same experimental setup than the abundances in Fig.3, are shown as dots in Fig.2. This interpretation of the strangeness data led to considerable discussions about whether the QGP had been found at the SPS or not [5]. It is interesting to note that models that assume a very hot thermally equilibrated hadron gas [6] seem to describe most of the features just as well as a QGP model [7]. Only for the heaviest hyperons the thermal hadron gas picture seems to fail. The QGP models can explain every ratio, but their assumptions regarding the plasma hadronization are very drastic and do not seem to be in agreement with a series of additional measurements for non-strange particle production. In particular, the QGP models require sudden hadronization, which means that the strange baryon abundances have to stay constant after hadronization. The kinematics of the hyperons can change through

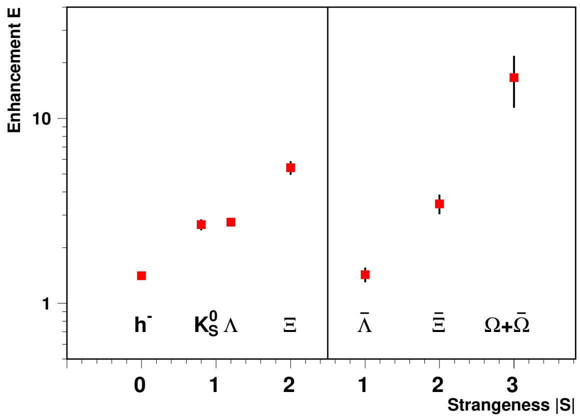

Figure 3. Strangeness Enhancement factors as measured by WA97 (from [4])

elastic rescattering with co-moving hadrons before thermal freezeout is reached, but the abundances and ratios which would be changed by inelastic scattering processes, are frozen. This is a drastic assumption in light of the fact that the system is very dense and that the cross sections for hadronic final state interactions are large. In a recent paper [8] we actually show that the probability of producing Λ's well after hadronization is quite large and should lead to a strong modification of any particle ratio that involved the Λ yield (see Fig.4).

Besides measuring the particle abundances and particle ratios additional information can be obtained from the kinematic spectra (transverse momentum and rapidity spectra). In particular, the inverse slope of the invariant cross section ($\sigma_{inv} \propto 1/p_T \, dN/dp_T$) as a function of transverse momentum, should, in the case of particle emission from a thermally equilibrated source, be related to the temperature of the source, based on Boltzmann statistics. Fig.5 shows the particle specific emission temperatures extracted from the measured transverse momentum spectra as a function of the particle mass [9]. The line indicates a simple scaling law that assumes that the emitting source is not at rest by taking into account the expansion velocity to calculate the 'real' emission temperature. Several thermal calculations (e.g. [10]) show that with a single expansion velocity for all particle species the transverse momentum spectra yield a common thermal freezeout tem-

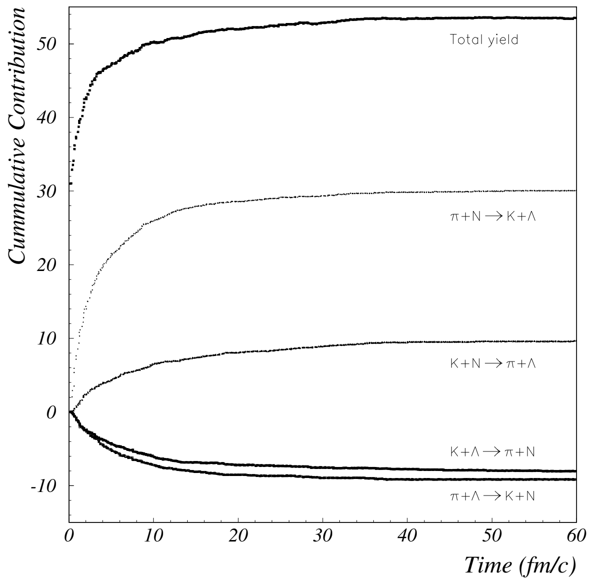

Figure 4. Contributions to the Λ yield after hadronization and before thermal and chemical freeze-out

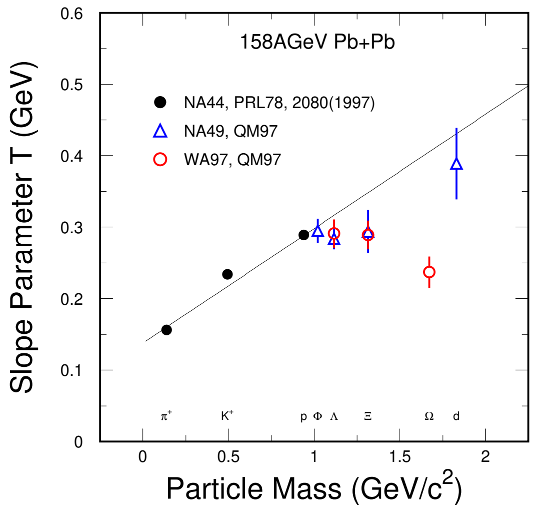

Figure 5. Inverse slope parameters (temperature) of particle identified transverse momentum spectra measured in CERN Pb+Pb collisions plotted against the particle mass (from [9])

perature for all particle species, see Fig.6.

Only the Ω particle strongly deviates from this collective behavior as shown in Fig.5. One possible explanation is that the Ω's decouple early from the fireball and thus do not 'flow' with the other emitted particles [9]. Still, the vast majority of the particle spectra indicate a common kinetic freezeout temperature T.

Taking this information together with chemical spectra (abundances, ratios) the situation is less clear,though. A typical ratio analysis is shown in Fig.7 on the basis of NA36 data [11]. This analysis is comparable to the determination of the temperature and expansion velocity through the kinetic spectra. Thermodynamically, the particle ratios carry additional information, though. They define the temperature and baryochemical potential phase space. The deduced temperature is higher than the thermal freezeout temperatures obtained from the particle ratios.

This discrepancy in calculated freeze-out temperature led to an interpretation that suggests that chemical freezeout is decoupled from kinetic freezeout and happens at an earlier stage.In essence this means that inelastic rescattering ceases before elastic rescattering. The phase transition picture in Fig.8 depicts our present understanding under the assumption that this simple thermal theory is correct [12].

Based on Fig.5 it seems that only the heaviest hyperons do not follow the general trend and decouple even kinetically early from the fireball (no boost in temperature due to the expansion velocity leads to lower temperature [9]) and thus are less susceptible to any kind of re-scattering which could potentially dilute any QGP signature. They also show the largest enhancements factors, which can be interpreted as a QGP signature. Still, the Ω measurements are not unambiguous in particular because of our understanding that the phase transition is a collective effect and should manifest itself in a variety of transition signatures. If one forms an event class of events that exhibit Ω enhancement, the other potential signatures do not seem to follow the hyperon trend. In summary, the present state of heavy ion measurements does not allow a definite conclusion regarding the formation of a plasma phase.

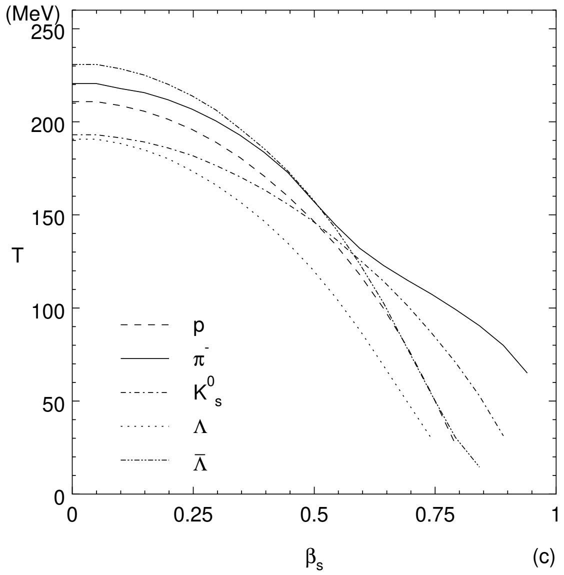

Figure 6. Calculation based on a thermal model [10] showing that all particle spectra can be described with a common emission temperature if a certain expansion velocity for the source is taken into account.

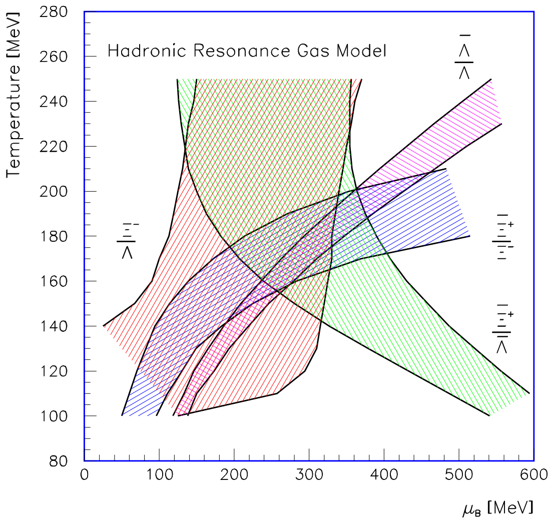

Figure 7. Thermal model analysis on the basis of strange particle ratios as measured by NA36

3. Λ Polarization

The study of hyperon polarization in relativistic heavy ion collisions is relevant not only as a comparison to the measurements in p-p and p-A reactions, but also as a potential, if indirect, QGP signature. Jacob and Rafelski [13] have suggested that the longitudinal polarization of the Λ in heavy ion collisions could be interpreted as a signature for an enhanced multi-strange hyperon production.

In addition the measurement of the transverse polarization in heavy-ion collisions might shed further light on the polarization production mechanism which seems to be independent of energy and system size [14].

The presently available Λ polarization measurements based on heavy-ion collisions are shown in Fig.9 in comparison to p-Be data. Both heavy ion measurements, taken in the late 80's by E810 [15] at the AGS and NA35 [16] at the SPS, respectively, lack the necessary statistical significance to determine the polarization level in the produced Λ's. In addition the momentum range covered might be too low to expect polarization based on the p-Be data. Thus, neither data set was ever published except in conference proceedings.

Experiment E896 at the AGS is presently analyzing Λ polarization in two different detectors [17]. More conclusive results should be available in the near future.

4. Λ Interferometry

A common analysis in heavy-ion collisions is the correlation of two or more identical particles emitted from a single source. This method is often referred to as HBT analysis [18]. Hanbury-Brown and Twiss used a similar analysis to measure the size of stars from the correlation function of the emitted photons. In the analysis the width of the correlation is inverse proportional to the size of the source. The method was quite successfully applied to the emission of pions, protons, and kaons from the fireball after a heavy-ion collision at AGS and SPS energies. Although the results leave room from many different interpretations, the data can be connected to the spatial extension of the thermally emitting source at kinetic freezeout. Due to the lack of statistics of events with two or more Λ's at the available incident energies it was never possible to measure

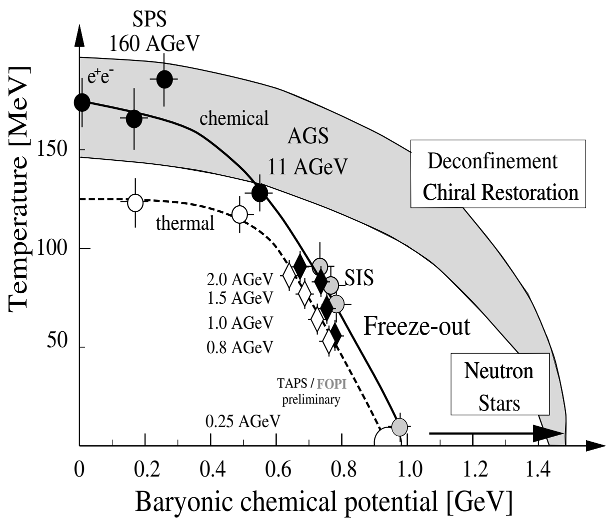

Figure 8. Phase transition plot on the basis of all available data from SPS, AGS, and SIS analyzed with a simple thermal model [12]

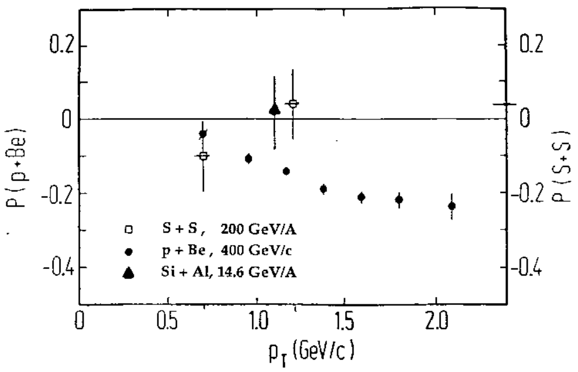

Figure 9. Preliminary low statistics heavy ion measurements of Λ polarization, in comparison to p+Be data. All presently available heavy-ion data are consistent with zero Λ polarization, but the statistics are low.

Λ correlations. Based on realistic event generators, though, the measurement should be possible at RHIC energies. Greiner and Mueller [19] have proposed several scenarios in which a difference in the Λ correlation function compared to e.g. the pion correlation function could be interpreted as a QGP signature or evidence for an enhanced strange quark matter generation probability. Very little is known about the Λ-Λ interaction and it seems that the resonant state that can be excited might affect the width and shape of the correlation function. But even in this case, a measurement of the resonance would shed new light on our understanding of the Λ interaction potential.

5. Search for Strange Quark Matter

Another even more speculative signature of a phase transition is the formation of strange quark matter [20]. Strange Quark Matter was postulated as a potential solution to the cosmological 'missing mass' problem [21].

Pure strange quark matter is comparable to hyperon clusters held together by an attractive binding energy. As a consequence of the bag model, Jaffe has postulated that the smallest hyperon cluster, namely the H-Dibaryon (udsuds) should be stable due to a color-magnetic attractive force. That means six-quark bags are possible within the standard model [22]. To be detectable as a particle the H mass has to be below the $\Lambda\Lambda$-mass, otherwise it might still exist as a resonance. It is not the ground state of conventional matter, thus it has to have a mass higher than the two neutron mass. Within this range of masses more than twenty accelerator based experiments have been performed. A nice summary can be found in [23]. Heavy ion data that suggest a set of H-Dibaryon candidates are described in [24]. Ongoing dedicated H experiments that employ higher resolution tracking devices focus on the H-mass region just below the Di-Λ mass, mainly because of recent discoveries of double strange hypernuclei, which exclude lower masses for the H [25]. In the remaining mass range the most likely decays are weak decays with a lifetime comparable to the Λ lifetime itself. The most prominent channel will be $H \rightarrow \Sigma^- p$ with a subsequent $\Sigma^- \rightarrow n\pi^-$ decay. A dedicated experiment (E896) has been built to search for short lived H-Dibaryons [17]. It features a Silicon Vertex Tracker as well as a Distributed Drift Chamber to cover different regions of phase space. The experiment took data in 1998 and is presently analyzing its data set, which should contain on the order of 200 reconstructible H-Dibaryons based on predictions by Dover et al. [27].

In recent years it was predicted by Greiner et al. [26] and Dover et al. [27] that in addition to possibly generating hyperon dibaryons, heavy ion reactions are particularly suitable to form so-called strangelets, clusters of many strange and light quarks that are held together in a single bag according to the bag model [20]. The main argument can be described as 'strange nucleosynthesis'. Greiner argues that a fireball with high particle density but relatively little energy density can generate a large number of hyperons in a small volume. In this case the hyperons can coalesce, simply by sufficient wavefunction overlap. The system is relatively cold, so there is little rapid expansion. In addition the existing baryon density caused by the stopping of the projectile in the target will cause the generated anti-strange quarks to combine with the existing light quarks to kaons which will be radiated off the fireball, whereas the strange quarks will stay in the fireball. This net strangeness will lead to enhanced hyperon production in a small volume. The penalty factors for hyperon coalescence were assumed to be comparable to simple baryon coalescence [27]. Recent measurements by the E864 Collaboration at the AGS, though, seem to indicate that there is an extra penalty factor for including a hyperon instead of a proton or neutron [28]. The group has measured the ${}^{3}_{\Lambda}H$ hyper nucleus and compared its production rate to the production of ${}^{3}He$. Based on these measurements it seems that the inclusion of a single hyperon leads to an additional penalty factor of about five. Thus, the original strangelet production rate predictions might be overly optimistic. Still, a variety of conclusive heavy-ion experiments have been performed or are still ongoing. E864 has set convincing upper limits to positive, neutral, and negative strangelet production. Their measurements are based on detecting a color-singlet configuration that has a mass of A = 10-15 amu and a small charge to baryon ratio. The detection method of choice is calorimetry in combination with a 'late energy trigger' to subtract background. Details can be found in [29]. Their strangelet limits (90% confidence level) vary between 10^{-9} and 10^{-7} depending on the charge state. No evidence for a strangelet has yet been found, but E864 is still analyzing data.

6. Future Measurements at RHIC

The main difference in stepping from fixed target experiments at AGS and SPS to the RHIC collider is the expected large increase in energy density in the collision [30]. Contrary to the fixed target experiments the probability of stopping will be drastically reduced, which means the two beams will be almost transparent to each other. That leads to a large energy density in the central collision region, but only a small baryon density. The initial temperatures will be higher, but the likelihood of forming a cold, particle dense plasma will be reduced. This has some implications on the various aspects of the RHIC hyperon program. The probability of forming strange quark matter might be reduced due to the high energy density and low particle density. In return the probability of enhancing and equilibrating strangeness might be increased. An interaction at RHIC is expected to undergo several distinct stages, beginning with a parton-parton interaction, followed by a parton cascade and finally a hadron cascade. It is unclear whether either cascade will lead to chemical equilibration, but the time before hadronization as well as the time for thermal equilibration after hadronization is enhanced. Geiger has shown that on the basis of the initial parton interaction, which will be dominated by gluonic processes, and the subsequent parton cascade, strangeness should be enhanced by an order of magnitude in the case of a QGP compared to a simple hadron gas scenario [2]. Strangeness equilibration will be more likely, simply due to the longer time the QGP will have to equilibrate. Estimates based on hydrodynamical models show that the hadronization time is expected to double (from about 8 fm/c to about 16 fm/c).

Based on these predictions, the RHIC hyperon program will initially be very similar to the just completed AGS and SPS programs. The main goal of the early measurements will be to establish the hyperon abundances, the hyperon-antihyperon ratios and the hyperon kinematic spectra. Although the particle production is much higher at RHIC than in the fixed target experiments we do not expect to generate hyperons at a rate that will allow us to measure their production on an event by event basis. Pions will be reconstructed by the thousands in each event, but the hyperon rate is still sufficiently small to require a many event sample for the spectra and the ratio measurements. The main detector for strangeness reconstruction is the STAR detector [32]. STAR is a typical cylindrical collider detector, featuring a large Time Projection Chamber (TPC) as its main tracking volume. The TPC is radially preceeded by a Silicon Vertex Tracker (SVT). This device with its superior position resolution and particle identification capabilities allows the reconstruction of all short lived hyperons up to the Ω. The SVT/TPC tracking combination resides in a 0.5 T solenoidal magnetic field and is backed up by an electromagnetic calorimeter (EMC) and a time-of-flight patch (TOFp) as well as a small ring imaging Cherenkov counter (RICH) for high momentum particle identification. The central tracker covers a pseudo-rapidity range $\eta=\pm1$. In forward direction STAR is equipped with two radial time projection chambers (FTPC) that extend coverage and possibly Λ reconstruction capabilities out to about $\eta=4$.

By combining the capabilities of the SVT and the TPC, hyperon reconstruction is sufficiently efficient to produce spectra within a short period of time during a RHIC running year (36 weeks/year). Figs.10 and 11 show the anticipated mass resolutions and accumulated statistics for Λ's and Ξ's, that can be obtained in 5 minutes and about a day of running, respectively.

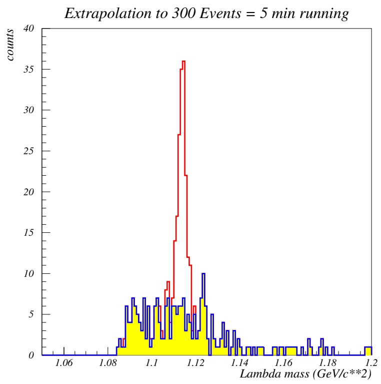

Figure 10. Λ mass reconstruction. Simulation result based on statistics comparable to a few minutes of RHIC running

The efficiency in the Λ reconstruction is sufficiently high to yield a good sample of events with more than one reconstructed Λ which will allow a correlation analysis based solely on Λ's. Even though there will be no event-by-event hyperon signature, the hyperon reconstruction will aid in specifying event classes with enhanced hyperon production. These classes will then be analyzed

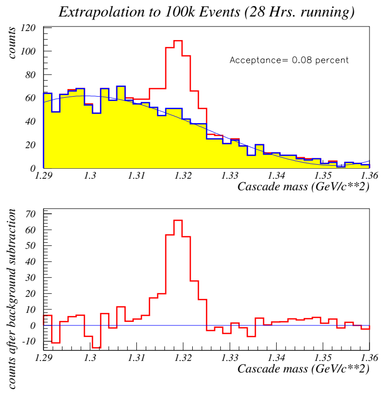

Figure 11. Ξ mass reconstruction. Simulation result based on statistics comparable to one day of RHIC running

for other potential QGP signatures, rather than having to analyze all recorded events.

Even though the probability for strange quark matter production based on coalescence type models might be reduced, the search for exotic forms of matter, like the strangelets or the H-Dibaryon will certainly be attempted. The tools are in place and the efficiency estimates show that it should be feasible to determine the probability of strange quark matter formation. A more detailed summary of the present state of strangeness related simulations for RHIC can be found in [31].

The results at RHIC will be groundbreaking. They will lead the field of relativistic heavy ion physics into an energy regime, where the transition into a new phase of matter is almost guaranteed as long as this phase really exists. Therefore even a negative result will be conclusive and lead to important ramifications for high energy, nuclear, and cosmological physics. We can all look forward to exciting results from the four experiments at RHIC: STAR [32], PHENIX [33], BRAHMS [34], and PHOBOS [35].

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