Strange Baryon Production From Nucleus-Nucleus Collisions at the AGS, SPS and RHIC

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Abstract.
We will present a review of selected results on strange baryon production from nucleus-nucleus collisions at the AGS, SPS and RHIC. From the AGS and SPS heavy ion physics program several intriguing aspects: centrality dependence of strangeness production, anti-hyperon yield, hyperon production enhancement and baryon number transport will be highlighted. Our discussion on RHIC results will focus on experimental probes of partonic degree of freedom. Measurements of the elliptic flow \( v_2 \) and the nuclear modification factor and their distinctive particle dependence are presented as a function of transverse momentum.

1. Introduction

Quantum ChromoDynamics (QCD) calculations on lattice predict the existence of the Quark Gluon Plasma (QGP), bulk matter of deconfined quarks and gluons [1]. The major scientific goal of the heavy ion collision physics is to create the QGP in high energy nucleus-nucleus collisions and to study QCD properties of the dense partonic matter. Strangeness, in particular strange baryon production, plays an important role both as a possible signature for the QGP formation and as a diagnostic probe of properties of the partonic matter. We will review experimental data on strange baryon production in nucleus-nucleus collisions within the context of studying production dynamics and bulk matter properties.

The production dynamics of strange baryons can reflect the nature of the partonic matter. It has been argued that gluon fusion processes are effective channels for strange quark pair production in the QGP leading to a rapid flavor equilibration such that the production of strange baryons can be significantly enhanced [2]. Strangeness equilibrium in a hadronic gas requires a much longer lifetime for the system; and this is dynamically unfavored in explosive high energy nucleus-nucleus collisions [3]. Finite net baryon density in nucleus-nucleus collisions at the AGS and SPS will also impact the strange baryon production dynamics. The elliptic flow \( v_2 \) and the nuclear modification factor will be used to probe properties of the matter at early stages of the nucleus-nucleus collisions. We will illustrate possible physical scenarios and production
dynamics using experimental data from the AGS, SPS and RHIC. The selection of the experimental data was based purely on convenient access of the data and was not meant to be comprehensive. We apologize to these collaborations whose data have been essential in deepening our understanding of the baryon production dynamics but are not explicitly highlighted in this paper.

We conclude this paper by listing several future measurements which will further elucidate the properties and particle formation dynamics for the bulk partonic matter.

2. Selected Topics at the AGS and SPS

In this section I will briefly discuss several unique physics themes from nucleus-nucleus collisions at the AGS and SPS and highlight the link between possible physical scenarios and experimental measurements.

Nucleus-nucleus collisions at the AGS and SPS are characterized by the formation of high net baryon density. Both the RQMD [4] and ARC model [5] have indicated that the initial net baryon density at the center of central Au+Au collisions at the AGS is very large, approximately ten times the normal nuclear matter density. One of the conceptual questions arising from such a large baryon density is the validity of description in theoretical calculations for hadron scatterings, since hadrons cannot exist as an independent entity in such a dense environment. The large baryon density at the initial stage also dictates the evolution dynamics of the collision: resonances, baryonic resonances in particular, are believed to play an important role for particle production and collective expansion in nucleus-nucleus collisions.

The large baryon density has a strong impact on the characterization of strangeness production in nuclear collisions. Strange and anti-strange quarks are produced pairwise in nuclear collisions. The strange quarks could eventually hadronize mostly through associate production ($\Lambda K^+$) and kaon pair production ($K^+K^-$). At high net baryon densities the Lambda ($\Lambda$) in the associate production carries the baryon quantum number from the colliding nuclei; and the energy threshold for the associate production in $N+N\rightarrow N\Lambda K^+$ is lower than that for the kaon pair production in $N+N\rightarrow NN K^+K^-$. The significant yield of $K^+$ from associate production would lead to a large ratio of $K^+/K^-$. Large $K^+/K^-$ ratios at mid-rapidity from Si+Si, Si+Au and Au+Au collisions at 14.6, 14.6, 11.7 AGeV incident beam energies, respectively, have been measured by the E802 collaboration [6]. The measured $K^+/K^-$ ratio varies from 5 to 7 with little dependence as a function of the number of participant nucleons. The variation in the ratio is largely due to the beam energy difference. A large number of $\Lambda$ hyperons, presumably from the associate production, has also been measured [7].

The intricacy of the dynamics in the high baryon density regime is reflected in the anti-Lambda ($\overline{\Lambda}$) to anti-proton ($\overline{p}$) ratios. Figure [1] shows the $\overline{\Lambda}$ to $\overline{p}$ ratios at $p_T\sim0$ for various centrality bins, which were derived from E864 and E878 $\overline{p}$ measurements [8]. The $\overline{\Lambda}$ to $\overline{p}$ ratio is significantly above unity for the most central Au+Pb collisions at 11.5 A GeV incident energy. A ratio greater than one was also obtained by the E917
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The preferred $\Lambda$ production over $\bar{p}$ could result from dynamics in a quark clustering scenario: a $ud$ diquark is more likely to find another $d$ quark to form a $\Lambda$ than to find another $u$ quark to form a $\bar{p}$ in nuclear collisions with high net baryon density where there is an excess of up and down quarks. The thermal statistical model of the QGP hadronization essentially depicts this scenario [11]. During the hadronic evolution the larger value for $\bar{p}$ annihilations [10] compared to $\Lambda$ annihilations could also lead to a large $\Lambda$ to $\bar{p}$ ratio in the final state.

Figure 1. Ratio of antihyperon to antiproton as a function of collision centralities for Au+Pb collisions at 11.5 A GeV incident energy. Arrows indicate the lower limit of the ratio at a 98% confidence level.

The production of strange baryons ($\Lambda$, $\Xi$ and $\Omega$) and their anti-particles has been observed to be strongly enhanced with respect to participant scaling at the SPS energies. Figure 2 presents the mid-rapidity strange baryon yield per participant (wounded nucleons), normalized to p+Be collisions, measured by the WA97/NA57 collaboration at the CERN SPS [12]. Similar enhancement factors have also been reported by the NA49 experiment [13]. The hyperon production per participant nucleon increases rapidly as a function of the number of participants. The magnitude of the enhancement increases with the strangeness content of the hyperons reaching approximately a factor of 20 for $\Omega + \Omega$ in central Pb+Pb collisions at 158 AGeV incident beam energy. The magnitude of the enhancement for $\Omega + \Omega$ is much larger than that for $\Lambda + \Xi$. Such an asymmetry between hyperons and anti-hyperons must be related to the finite net baryon density at mid-rapidity in nuclear collisions at the SPS. The fragmentation of colliding nuclei into hyperons is one possible process for the rapid increase of hyperon yield as suggested by E910 [14]. However, the significant enhancement of anti-hyperon production per participant indicates that the baryon pair production probability also increases in central collisions.

The fragmentation of the colliding nuclei also contributes to the baryon number transport in nuclear collisions [15]. The anti-baryon to baryon ratio from a system with finite net baryon density would be deviate from unity. Figure 3 shows the anti-baryon to baryon ratio as a function of the strangeness content of baryons from central Pb+Pb (SPS) and Au+Au (RHIC) collisions. The ratios are much closer to unity at the RHIC
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Figure 2. Mid-rapidity strange baryon yield per participant nucleon normalized to p+Be collisions measured by NA57 at the SPS. The enhancement factor increases rapidly with the increasing strangeness content from Λ to Ω.

energies indicative of a much smaller net baryon density.

Figure 3. Anti-baryon to baryon ratios from central Pb+Pb (SPS) and Au+Au (RHIC) collisions as a function of the strangeness content of baryons.

A comment on the $\Omega$ to $\Omega$ ratio at the SPS energy is in order. The ratio is approximately 0.4, significantly different from unity. This indicates that at mid-rapidity there are 2.5 times more $\Omega$ than $\overline{\Omega}$. Such a large asymmetry probably reflects intriguing underlying dynamics because strange quarks in $\Omega(\bar{s}ss)$ and $\overline{\Omega}(\bar{s}ss)$ must be produced in pairs in nuclear collisions. The excess of baryon number in $\Omega$ over $\overline{\Omega}$ at mid-rapidity is unlikely to be balanced by $\overline{\Omega}$ at the forward and backward rapidity regions, since this would lead to a much wider rapidity distribution for $\overline{\Omega}$. In fact, the NA49 experiment reported a rapidity width for $\overline{\Omega}$ slightly narrower than that for $\Omega$. The excess of $\Omega$ hyperons is likely to carry the baryon numbers from the colliding nuclei. The dynamical process for baryon number transport from incoming protons and neutrons to $\Omega$ hyperons which share no up and down valence quarks, is a subject of intensive theoretical and experimental investigations. Possible scenarios include direct baryon
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number transport through gluon junction interaction and indirect transport through baryon pair production.

Figure 4 depicts a schematic diagram for baryon number transport through gluon junction interaction. Under strong coupling limit the gluon strings which are used to model the interactions among valence quarks take the junction configuration [16]. In nuclear collisions if all three gluon strings are broken up, then the baryon quantum number is transported by the gluon junction. The probability for such gluon junction interactions could be significantly enhanced in nucleus-nucleus collisions leading to a larger degree of baryon stopping at mid-rapidity [17]. For the $\Omega$ to be produced from the gluon junction interaction and carry the baryon number from colliding nuclei multiple kaons must also be produced. The correlation of these kaons with the $\Omega$ provides a unique experimental signature for this process.

![Figure 4. Schematic illustration of a baryon in gluon junction configuration. An $\Omega$ hyperon can carry the original baryon quantum number if the $\Omega$ is produced during gluon junction interaction where three pairs of $s$-$\bar{s}$ quarks are created from the gluon string break-upps. Multiple kaons must also be produced in the process.](image)

Hyperon pair production can proceed through channels of $\Omega-\bar{\Omega}$ or $\Omega-\Xi K$, $\Xi-\bar{\Xi}$ or $\Xi-\bar{\Lambda} K$, and $\Lambda-\bar{\Lambda}$ or $\Lambda-p K$. The kaon associated channels are normally suppressed compared to the other due to a higher energy threshold. However, the presence of finite net baryon density could modify the relative fraction of these channels. The $\bar{\Omega}$ to $\Omega$ ratio of 0.4 would indicate that the $\Omega-\Xi K$ channel is enhanced over the $\Omega-\bar{\Omega}$ channel for $\Omega$ production at mid-rapidity if these channels dominate the $\Omega$ production. Measurements of correlations among $\Omega$, $\Xi$ and kaons can shed light on the production dynamics.

3. Strange Baryon Production at RHIC

The yield of $\Lambda$ and $\bar{\Lambda}$ production at RHIC was first reported by STAR [18] and PHENIX [19] for Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. The measured rapidity density ($dn/dy$) of $\Lambda$ and $\bar{\Lambda}$ depends linearly on the pseudo-rapidity density of negatively charged hadrons. The linear dependence of the baryon rapidity density on charged hadrons (mostly pions) is also a feature in baryon production models based on string fragmentations. However, in fragmentation models such as HIJING [20] the yields of strange hyperons are greatly suppressed: the HIJING model produces too many anti-protons and too few $\Lambda$ and $\bar{\Lambda}$ hyperons. The discrepancy between data and the fragmentation model calculation is even larger for multi-strange hyperons. By introducing final state interactions between co-moving hadrons or partons from densely
populated interacting strings, the yield of multiple-strange hyperons can be significantly enhanced from primordial string fragmentation processes [21]. The most effective reactions are $\pi N \rightarrow K \Lambda(\Sigma)$, $\pi \Lambda(\Sigma) \rightarrow K \Xi$, $\pi \Xi \rightarrow K \Omega$ and their respective anti-particle reactions.

In addition, multi-parton dynamics such as gluon junction hadronization [16, 17], quark coalescence [22, 23, 24] and parton recombination [25, 26] have been applied to strange baryon production. Since based on parton structure functions of nuclei gluons are expected to be mainly responsible for the formation of the initial high energy density matter in nucleus-nucleus collisions at RHIC, the mechanism of gluon junction hadronization for baryon production is an intriguing scenario. With the formation of a high density gluonic fireball, the gluon junction depicted in Figure 4 would naturally be a possible topological configuration existing inside the fireball. Then the simultaneous breakups of the three gluon strings of the junction would lead to the formation of a baryon or an anti-baryon. In such a formation scheme the mass of the baryon could come mainly from the gluon junction and the flavor of the baryon would be determined by the light quark pair from the gluon string breakup. As a result the production probability of multiple strange hyperons would not be significantly suppressed. In the normal string fragmentation mechanism for baryon production hyperons are strongly suppressed due to small tunneling probability for the higher mass diquarks of the hyperons [27, 28]. In quark coalescence or quark recombination scenarios, if the initial quark (e.g., constituent quarks in ALCOR model [29]) matter has sufficiently large number of strange quarks available, the production of high mass hyperons can also be enhanced. In all these scenarios the formation of baryons requires the interaction of multiple gluons or quarks (partons) in contrast to standard single parton fragmentation where the rest of the baryon constituents being treated as out of vacuum.

Identified particles, especially with comparisons between baryons and mesons, provide a unique means to investigate possible formation dynamics from the partonic perspective and to examine properties of the partonic matter carried by hadrons in the final state [30, 31, 32]. Figure 5 shows $v_2$ as a function of transverse momentum $p_T$ for $K_S$, $\Lambda+\bar{\Lambda}$ and charged hadrons from minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $v_2$ of heavy particles $\Lambda+\bar{\Lambda}$ is smaller than that of light $K_S$ in the low $p_T$ region below 1.5 GeV/c. This $v_2$ ordering of particle dependence is consistent with hydrodynamical calculations where parton thermalization and collective expansion velocity driven by a pressure gradient are assumed. Note that inclusive transverse momentum distributions of identified pions, kaons and protons at low $p_T$ can also be described in this framework, for example using a blast-wave parameterization for collective motions [33].

At the intermediate $p_T$ above 2 GeV/c, however, the $v_2$ of hyperons is larger than that of $K_S$ and the magnitude of $v_2$ shows little $p_T$ dependence. Both features are in contradiction with hydrodynamical calculations [34]. A $p_T$ independent $v_2$ may result from particle emission from the surface of an ellipsoid formed in nucleus-nucleus collisions [35]. A surface emission scenario can be accommodated dynamically if at the time of the particle emission the source is at sufficiently high density and opaque.
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Anisotropy Parameter $v_2$

Figure 5. Elliptic flow $v_2$ as a function of transverse momentum for $K_S$, $\Lambda + \bar{\Lambda}$ and charged hadrons from minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Predictions of hydrodynamical calculations for identified particles are shown for comparison.

If the particle formation is through the fragmentation of high $p_T$ partons which have undergone partonic energy loss in the medium, the large $v_2$ of hyperons would imply a larger energy loss for partons of hyperon production than those of kaons.

Figure 6 shows the nuclear modification factor ($R_{CP}$) derived from ratios for particle yields of central to peripheral collisions normalized to the number of binary collisions, for hyperons and kaons, where

$$R_{CP} = \frac{[d^2n/(N_{\text{binary}}dp_Tdy)]_{\text{central}}}{[d^2n/(N_{\text{binary}}dp_Tdy)]_{\text{peripheral}}}.$$  

Details of the measurement can be found in references [31, 36, 37, 38]. The suppression of particles at the intermediate $p_T$ region with respect to the binary collision scaling is much smaller for hyperons. In fact, there is an absence of suppression for hyperons for $p_T$ from 1.8 to 3.5 GeV/c whereas the kaons are suppressed over all $p_T$. If the nuclear modification is dominated by the process of partonic energy loss followed by parton fragmentation, then the smaller suppression of the hyperons would imply a smaller energy loss, contradicting the larger energy loss needed for a greater $v_2$.

Distinctive $p_T$ scales associated with different dynamical processes in nucleus-nucleus collisions at RHIC have been observed: parton fragmentation at $p_T$ greater than 6 GeV/c where a suppression of particle yield with respect to binary collision scaling has been observed [39, 40]; and hydrodynamical behavior at $p_T$ less than 2 GeV/c. The intermediate $p_T$ region of 2 to 6 GeV/c is uniquely sensitive to multi-parton dynamics, such as gluon junction hadronization for baryons [17], quark coalescence [23, 24] and parton recombinations [25, 26]. That sensitivity may be reflected in the elliptic flow $v_2$ and nuclear modification factor measurement. In a quark coalescence or recombination scenario the elliptic flow of a particle results from an anisotropical angular distribution of individual quarks/partons at the time of hadron formation; and the nuclear modification factor measures the dependence of particle formation probability on the parton density.
In these scenarios it is natural to expect the baryon formation probability to depend on higher powers of parton density than mesons. Therefore, the yield of baryons in the intermediate $p_T$ region increases faster than that of mesons from peripheral to central collisions. Recent STAR\cite{38} and PHENIX\cite{41} measurements reveal qualitatively an important contribution of multi-parton dynamics in the intermediate $p_T$ region.

To establish the exact dynamical scenario requires more experimental measurements on a variety of hyperons and mesons and deeper theoretical understanding of the hadronization phenomenology.

4. Perspective

RHIC as a dedicated nuclear QCD research facility at high energy has provided a unique opportunity to study partonic dynamics in nucleus-nucleus collisions. Experimental data from RHIC have shown prominent features consistent with collective partonic dynamics, which are absent or overwhelmed by hadronic features in low energy data. In nucleus-nucleus collisions at RHIC we can identify three distinct $p_T$ scales: the hydrodynamic region below 2 GeV/c where properties of bulk matter due to interactions at the partonic phase or the hadronic phase or both are important; the fragmentation region above 6 GeV/c where particle production through parton fragmentation may become dominant; and the intermediate $p_T$ region of 2 to 6 GeV/c where multi-parton dynamics may be prominent with enhanced sensitivity to partonic properties of the bulk matter. We will list several future measurements which will shed light on both the transition among
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these $p_T$ regions and the underlying dynamics of partonic nature.

The STAR $v_2$ and $R_{CP}$ measurements of $\Lambda + \bar{\Lambda}$ and $K_S$ along with charged hadrons indicate that the particle dependence of the nuclear modification factor disappears for $p_T$ greater than 5-6 GeV/c. The jet quenching phenomenon \cite{20}, if it is proven to be applicable at the high $p_T$ region, will provide a unique probe of the dense matter at the initial stage of nuclear collisions. The angular anisotropy $v_2$ for identified particles in this high $p_T$ region is an important measurement to establish the validity of the pQCD-inspired fragmentation approach for particle production. The combination of $v_2$ and nuclear modification factor measurements for identified particles above $p_T$ 6 GeV/c can provide quantitative constraints on possible energy loss of partons through a dense hot QCD medium.

In order to verify the possible geometrical origin of the $p_T$ independent saturated $v_2$ value, it is important to measure elliptic flow at intermediate $p_T$ from light ion collisions. In collisions of light ions the surface to volume ratio should be very different from Au+Au collisions which may lead to a different $p_T$ dependence for $v_2$. The nuclear modification factor in light ion collisions may also be different and systematic studies of $A$ dependence may lead to better quantitative measures related to the physical origin of the high $p_T$ suppression.

Particles with small hadronic rescattering cross sections suffer small final hadronic interactions with co-moving hadrons and therefore may carry the information of matter properties at the particle formation time. It is generally believed that $\phi$ meson, $\Omega$ ($\Xi$ and $\Lambda$) and heavy quark particles (mostly $D$ mesons at RHIC) satisfy the requirement for small hadronic cross sections and can be used to probe partonic matter properties \cite{42}. Note that the information derived from these particles provides a snapshot of the matter properties at the particle formation time, the so called chemical freeze-out time, which lies at the phase boundary between quarks and hadrons. Such snapshot information complements that from the electromagnetic probes such as leptons which provide a time-integrated evolution history of the dense matter. A vigorous program to measure $v_2$ and the nuclear modification factor for $\phi$, $\Omega$ and $D$ particles is being pursued.

Identified particle correlations over a large $\Delta y$-$\Delta p_T$ scale such as those among $\Omega$-kaons and $\Omega$-$\Xi$ will shed important insight on possible roles of multi-parton dynamics in nucleus-nucleus collisions at RHIC. The gluon junction interaction and its possible role in baryon number transport and baryon production remains an intriguing theoretical suggestion. In order to carry out these correlation measurements at RHIC with STAR, several upgrades are required such as the barrel Time-of-Flight detector, the micro-Vertex detector and improvements in the TPC front-end electronics and data acquisition system.

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