SELECTED HIGHLIGHTS FROM THE STAR EXPERIMENT AT RHIC*

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(Received September 30, 2010)

We review selected highlights of the STAR experiment at RHIC, focusing on results on strangeness production, elliptic flow and the recent discovery of antihypertriton in Au + Au collisions at 200 GeV. While the hypertriton has been discovered earlier by other experiments, antihypernuclei have never been observed. This result extends the nuclear chart into antimatter with strangeness.

PACS numbers: 13.20.Ft, 13.20.Hw, 12.38.–t, 25.75.–q

1. Introduction

One of the main programs of the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven Laboratory, USA, is the exploration of the QCD phase diagram using heavy ion collisions up to $\sqrt{s}_{NN} =$ 200 GeV as well as using $p+p$ and $d+$Au collisions as a baseline for comparisons to $A+A$ collisions, to prove predictions of Quantum Chromodynamics. It has been estimated that in central Au + Au collisions at $\sqrt{s}_{NN} = 200$ GeV, the initial Bjorken mean energy density reached, is about 5 GeV/fm^3, therefore higher than the critical energy density predicted by lattice QCD for the QCD phase transition between hadronic matter and deconfined quark and gluon matter. Furthermore strong collectivity has been observed, suggesting that the high density partonic source built in the initial state of the collision is strongly interacting, noted in short as sQGP: strongly interacting Quark Gluon Plasma.

* Presented at the Workshop "Excited QCD 2010", Tatranská Lomnica/Stará Lesná, Tatra National Park, Slovakia, January 31–February 6, 2010.

The STAR experiment has as a main detector a large Time Projection Chamber (TPC) with full acceptance in the azimuthal angle and covering midrapidity, placed in a magnetic field of up to 0.5 T. STAR allows for particle identification of many particles in a large acceptance. Details on the STAR detector can be found in [1].

We focus on three particular aspects of STAR physics, namely strangeness production, elliptic flow and the observation of antihypertritons. Strange particle enhancement is one of the proposed signatures of the QCD phase transition, and we discuss here previous results in the light of new phi measurements of STAR. We discuss an important result of STAR, namely the scaling of the elliptic flow with the number of quarks, and address the question if the ideal hydrodynamic limit is reached. Furthermore, we present the recent data on the antihypertriton discovery which extends the nuclear chart into antimatter with strangeness. At the end, we give a glimpse into future plans of STAR, in particular, on the RHIC low energy scan, searching for the critical point for the QCD phase transition, as well as future plans for exotics searches.

2. Strangeness and elliptic flow

An enhancement in strange particle production in the Quark Gluon Plasma (QGP) formed in heavy ion collisions as compared to $p+p$ collisions was one of the early predictions of QGP signatures [2]. One of the problems to consider in the interpretation of this enhancement as signature of QGP, has been the prediction of canonical suppression of strangeness in the small $p+p$ collision system [3]. We discuss in the following STAR's contributions to the understanding of this issue through the measurement of the enhancement of the phi meson.

Fig. 1, upper panel shows the ratio of the yields of K^-, ϕ, $\bar{\Lambda}$ and $\Xi+\bar{\Xi}$ normalized to the number of participant nucleons ($\langle N_{\rm part}\rangle$) in Au + Au collisions at 200 GeV, and of the ϕ in Cu + Cu collisions at 200 GeV to corresponding yields in $p+p$ collisions at 200 GeV as a function of $\langle N_{\rm part}\rangle$. The lower panel of the same figure shows the same ratio as before for ϕ mesons in Cu + Cu and Au + Au collisions at 62.4 and 200 GeV. Error bars represent statistical and systematic errors added in quadrature [4].

The enhancement of K^-, $\bar{\Lambda}$, $\Xi+\bar{\Xi}$ and ϕ mesons (see [4] and references therein) is seen in Fig. 1 as an increase in the yield of strange particles per participant nucleon in nucleus–nucleus collisions as compared to the same ratio in $p+p$ collisions.

Canonical suppression models predict the strangeness enhancement to increase with the number of strange quarks, and while this trend is seen in Kaons, Lambdas and Xis, it is not observed in the phi (Fig. 1). The difference in the ordering does not seem to be a baryon–meson effect, since

K^- and $\bar{\Lambda}$, namely a meson and an antibaryon, have similar enhancement, neither a mass effect, since ϕ and $\bar{\Lambda}$ have similar mass but different enhancement. Furthermore, canonical suppression models predict the strangeness enhancement to decrease with increasing energy, while the ϕ enhancement is increasing with increasing energy (Fig. 1). The ϕ having zero net strangeness is not subject to canonical suppression in $p+p$ collisions therefore ϕ enhancement cannot be attributed to canonical suppression in $p+p$ collisions.

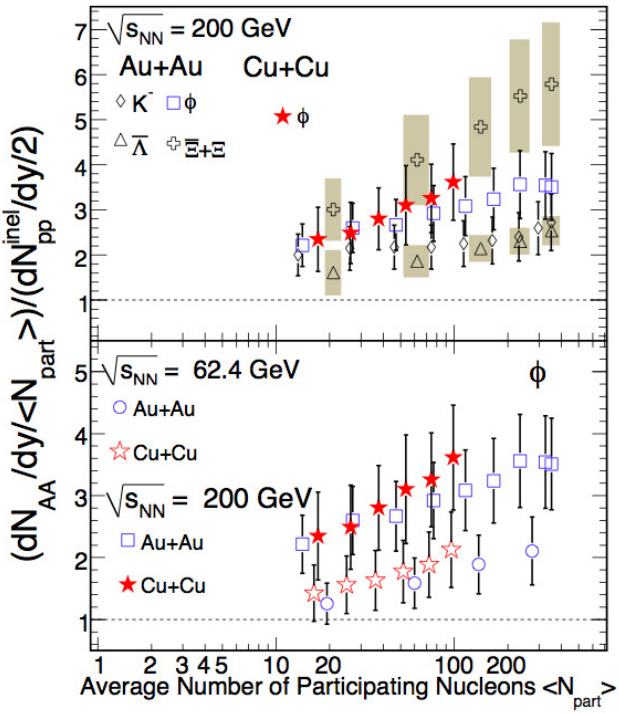

Fig. 1. Upper panel: The ratio of the yields of K^-, ϕ, $\bar{\Lambda}$ and $\Xi + \bar{\Xi}$ normalized to $\langle N_{\rm part}\rangle$ in $A+A$ collisions to corresponding yields in $p+p$ collisions at 200 GeV as a function of $\langle N_{\rm part}\rangle$. Lower panel: The same as above for ϕ mesons in Au + Au and Cu + Cu collisions at 62.4 and 200 GeV. Error bars represent statistical and systematic errors added in quadrature.

Furthermore, $p+p$ collisions at 200 GeV are at an energy which is 25 times higher than energies where violations of the OZI rule were reported [5]. Also the centrality dependence of the phi enhancement shown in Fig. 1 suggests that this enhancement is not due to OZI suppression in the $p+p$ collisions at 200 GeV.

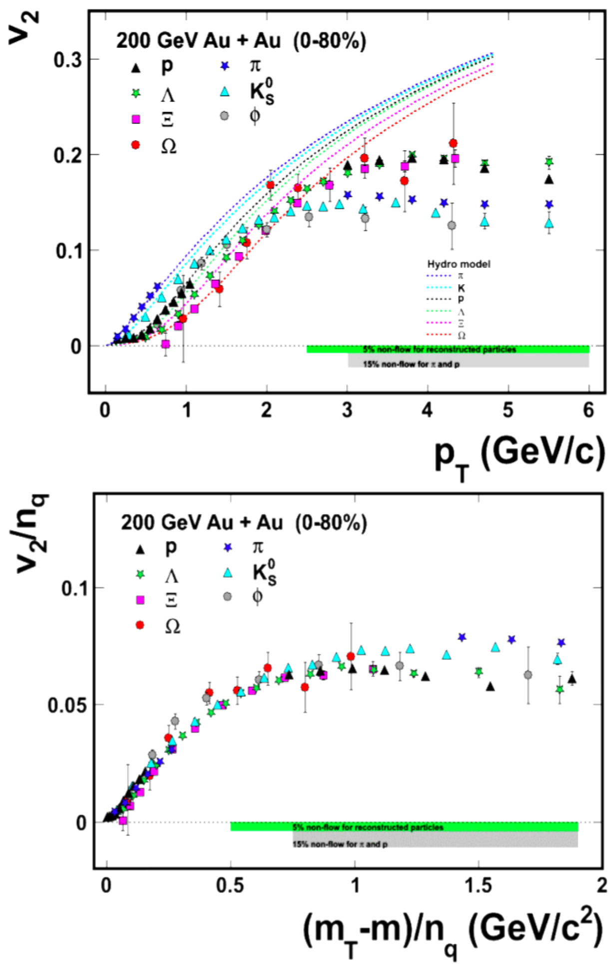

Fig. 2. Upper panel: Elliptic flow coefficients (v_2) as a function of $p_{\rm T}$ for 0–80% centrality Au + Au collisions at 200 GeV. Lower panel: Elliptic flow coefficients (v_2) divided by the number of valence quarks (n_q) as a function of $(m_{\rm T} - m)/n_q$.

From the above we conclude that the enhancement of the phi in $A + A$ collisions with respect to $p+p$ collisions at RHIC demonstrated in Fig. 1 is a consequence of the formation of a dense partonic medium in heavy ion collisions at RHIC and not to canonical suppression neither to OZI suppression in $p + p$ collisions. The same should then apply to explain the enhancement of all other strange particles produced in heavy ion collisions at RHIC.

Collective flow reflects the dynamical evolution in the early stage of high-energy heavy ion collisions [6]. The initial spatial anisotropy of the overlap region of the colliding nuclei is transformed into an anisotropy in momentum space through particle interactions. The magnitude of this effect is characterized by the elliptic flow defined as $v_2 = \langle \cos 2(\phi - \Psi_\mathrm{R}) \rangle$, with ϕ the azimuthal angle of a produced particle and Ψ_R the azimuthal angle of the impact parameter. Angular brackets denote an average over many particles and events. An interesting feature of v_2 measurements is the so-called number of constituent quark scaling [7]. Recent results on this phenomenon are shown in Fig. 2, where the upper panel shows the transverse momentum (p_T) dependence of v_2 for several hadrons in Au + Au collisions at 200 GeV, while the lower panel shows the same divided by the number of constituent quarks n_q. The mass hierarchy of these particles at low $p_\mathrm{T} < 1$ GeV can be reproduced by hydro calculations [8]. The scaling with the number of constituent quarks seems to hold up to $(m_\mathrm{T} - m)/n_q < 1$ GeV. Even though ϕ and Ω experience less hadronic rescattering they show similar v_2 p_T dependences [9]. The above results suggest strongly that elliptic flow measurements are a strong indication of partonic collectivity.

An additional probe of interest is the fourth harmonic of the Fourier expansion of the azimuthal distribution of particles [10]. Fig. 3 shows the ratio v_4/v_2^2 as a function of p_T in Au+Au collisions at 200 GeV [11] together with the prediction of hydrodynamic calculations from [12]. The deviation seen between the model and the data in this figure indicates that ideal hydrodynamics do not describe heavy ion collisions at 200 GeV.

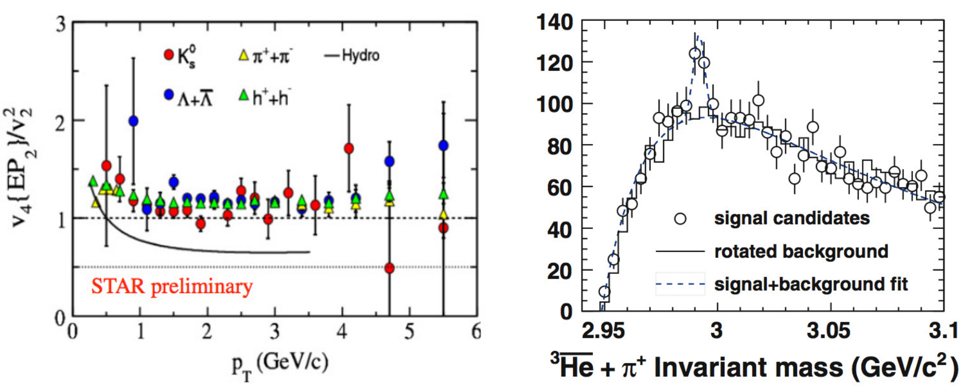

Fig. 3. Left panel: The flow coefficients v_4/v_2^2 as a function of p_T for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [11]. The solid line corresponds to the result of hydrodynamic calculations from [12]. Right panel: Invariant mass distribution of $^3\overline{\mathrm{He}}$ and π^+. Open circles is the signal candidates distribution, while solid (black) lines are background distributions. Dashed (blue) lines are fits to the data using a Gaussian for the signal and a background combined fit [13].

3. Observation of antihypertritons in Au + Au collisions

The STAR experiment has recently measured the first antihypernucleus ever seen, namely the antihypertriton which contains an $\bar{p}$, an $\bar{n}$ and an $\bar{\Lambda}$ as well as the hypertriton which contains a proton, a neutron and a Λ particle in Au + Au collisions at 200 GeV. Final results of this study have been published in [13] and preliminary results in [14–16].

The antihypertriton has been reconstructed by the invariant mass of its decay products $\overline{^3\mathrm{He}}$ and π^+ (BR 25%). The decay products $\overline{^3\mathrm{He}}$ and π^+ were identified by correlating the $\langle dE/dx \rangle$ values of charged particles in the STAR TPC with their measured magnetic rigidity and the secondary vertex of the decay has been reconstructed. Several topological cuts have been applied to improve the signal to background ratio like, for example, the distance between the daughters (< 1 cm), the distance of closest approach (DCA) between the $\overline{^3\mathrm{He}}$ candidate and the primary vertex of the interaction (< 1 cm), and the decay length of the antihypernucleus (> 2.4 cm).

Fig. 3 right panel, shows the invariant mass of the $\overline{^3\mathrm{He}}$ and π^+. The statistical significance for the antihypertriton measurement is $4.1\,\sigma$, while for the hypertriton it is $5.2\,\sigma$. The lifetime measured from the combined hypertriton and antihypertriton sample is found to be $\tau = 182^{+89}_{-45} \pm 27$ ps, which is comparable to that of the free Λ hyperon within errors. Table I shows particle ratios measured in Au + Au collisions at 200 GeV. The ratio of antihypertriton to antihelium-3 and the ratio of hypertriton to helium-3 are both close to unity. They are, therefore, significantly larger than the ratio of hypertriton to helium-3 measured at lower energies [13]. The antihypernucleus measurement extends for the first time the chart of nuclides into antinuclei with nonzero strangeness and demonstrates that RHIC is a unique source of exotic hypernuclei and antinuclei.

TABLE I

Particle rations from Au + Au collisions at 200 GeV [13].

Particle type	Ratio
$\overline{^3_{\bar{\Lambda}}\mathrm{H}}/^3_{\Lambda}\mathrm{H}$	$0.49 \pm 0.18 \pm 0.07$
$\overline{^3\mathrm{He}}/^3\mathrm{He}$	$0.45 \pm 0.02 \pm 0.04$
$\overline{^3_{\bar{\Lambda}}\mathrm{H}}/\overline{^3\mathrm{He}}$	$0.89 \pm 0.28 \pm 0.13$
$^3_{\Lambda}\mathrm{H}/^3\mathrm{He}$	$0.82 \pm 0.16 \pm 0.12$

4. Summary and outlook

We discussed selected highlights of the STAR experiment at RHIC: The ϕ meson enhancement rules out the canonical suppression as a source of strangeness enhancement in heavy ion, as compared to $p + p$ collisions at RHIC. The number of constituent quark scaling of the elliptic flow dependence on transverse momentum of several hadrons including the ϕ and the Ω which can be reproduced by hydrodynamic calculations at low $p_{\rm T}$ (< 1 GeV), are a strong indication of partonic collectivity. The above results suggest strongly the formation of a dense partonic medium in heavy ion collisions at RHIC. The deviation of the ratio v_4/v_2^2 as a function of $p_{\rm T}$ in Au + Au collisions at 200 GeV from prediction of hydrodynamic calculations indicates that ideal hydrodynamics do not describe heavy ion collisions at 200 GeV. Finally, STAR reported the first antihypernucleus ever seen, in particular the antihypertriton in Au + Au collisions at 200 GeV as well as the hypertriton. The ratio of antihypertriton to antihelium-3 and of hypertriton to helium-3 are both close to unity, and are significantly larger than the ratio of hypertriton to helium-3 measured at lower energies. The antihypernucleus measurement extends for the first time the chart of nuclides into antinuclei with nonzero strangeness and highlights RHIC as a unique source of exotic hypernuclei and antinuclei.

STAR plans for the future include an improvement in the statistics for (anti)hypertritons, new hypernuclei measurements, and search for anti-α is planned. Furthermore, STAR has plans to search for glueball production in double pomeron exchange processes in polarised $p + p$ collisions by means of Roman Pots [17]. Future plans with the new STAR Heavy Flavour silicon Tracker have been discussed in other talks of this conference. Furthermore, STAR is underway to explore the QCD phase diagram [18] with a low energy scan and search for the critical point through measurements of direct signatures like fluctuations [19] as well as turning off already established sQGP signatures at RHIC [20].

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