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Enhanced strange baryon production in Au+Au collisions compared to $p+p$ at $\sqrt{s_{NN}} = 200$ GeV

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We report on the observed differences in production rates of strange and multistrange baryons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared to $p+p$ interactions at the same energy. The strange baryon yields in Au+Au collisions, when scaled down by the number of participating nucleons, are enhanced relative to those measured in $p+p$ reactions. The enhancement observed increases with the strangeness content of the baryon, and it increases for all strange baryons with collision centrality. The enhancement is qualitatively similar to that observed at the lower collision energy $\sqrt{s_{NN}} = 17.3$ GeV. The previous observations are for the bulk production, while at intermediate p_T, $1 < p_T < 4$ GeV/c, the strange baryons even exceed binary scaling from $p+p$ yields.

I. INTRODUCTION

One of the aims of studying relativistic heavy ion collisions is to observe how matter behaves at extremes of temperature and/or density. The energy densities in the medium produced by these collisions are far from that of ground state nuclear matter. Ultimately we hope to determine if they are sufficiently high to create a system where the degrees of freedoms are those of quarks and gluons, a state called the quark-gluon plasma (QGP). By comparing the particles produced in $A+A$ to those from $p+p$ collisions, in which a QGP phase is not expected, we can gain insight into the properties of the medium.

Strange particles are of particular interest since the initial strangeness content of the colliding nuclei is very small and there is no net strangeness. This means that all strange hadrons must be formed in the matter produced. Originally, it was proposed that strangeness production would be increased due to the formation of a QGP compared to that from a hadron gas [1]. This enhancement is due to the high production rate of $gg \to s\bar{s}$ in a QGP, a process absent in the hadronic state. The subsequent hadronization of these (anti)strange quarks results in a significant increase in strange particle production, thus signaling a plasma was formed.

The concept of enhanced strangeness production in the QGP can be recast in the language of statistical mechanics. A grand canonical ensemble limit is likely only to be reached in the high multiplicity of heavy ion reactions. If this is the case, any measured enhancement is really a phase-space suppression in $p+p$ reactions that is removed in the heavy ion case. This lack of available phase space in small systems, such as those from $p+p$ collisions, requires a canonical ensemble to be used, which results in a suppression of strangeness production when scaled to the appropriate volume [2,3]. However, there is no *a priori* method for directly calculating this volume, and thus the authors make the simplest hypothesis and assume that the volume is linearly proportional to the number of collision participants $\langle N_{\mathrm{part}} \rangle$. The degree of suppression increases with the strange quark content of the particle. For sufficiently large volumes, the system is thermalized, the phase-space suppression effects disappear, and the yields scale linearly with the volume, i.e., $\langle N_{\mathrm{part}} \rangle$. Initial measurements from the CERN Super Proton Synchrotron (SPS) suggested such a linear $\langle N_{\mathrm{part}} \rangle$ scaling [4]. However, it is not observed in measurements made at the BNL Relativistic Heavy Ion Collider (RHIC) [5] or in the more recent SPS results [6].

While the observables mentioned above are sensitive to the bulk of the produced particles with momenta below 2 GeV/c, further important information can be extracted from intermediate and high p_T particles. At RHIC, hadrons are suppressed at intermediate to high p_T when compared to binary-scaled $p+p$ data at the same energy [7]. This effect is attributed to the energy loss of partons as they traverse the hot and dense medium produced [8,9]. Measurements using identified particles help shed light on the details of the energy loss mechanism.

II. ANALYSIS

In this paper, we present further analysis of the high statistics measurements from $p+p$ and Au+Au colli-

sions at $\sqrt{s_{NN}} = 200$ GeV for strange and multistrange baryon production at midrapidity as reported by the STAR Collaboration at RHIC [5,10]. Details of the STAR experiment are in Ref. [11]. Specific details of the trigger and detectors used to collect the data reported here can be found in Refs. [5,10] and references therein. The Au+Au event sample consisted of 1.5×10^6 central collision triggers and 1.6×10^6 minimum bias triggers. The $p+p$ results are from 6×10^6 minimum bias events. Particle identification is via the reconstruction of the charged daughter decay particles in the time projection chamber. The decay channels used are $\Lambda \to p + \pi^-$, $\Xi^- \to \Lambda + \pi^- \to p + \pi^- + \pi^-$, and $\Omega^- \to \Lambda + K^- \to p + \pi^- + K^-$ plus the charge conjugates for the antiparticle decays.

After cuts, to reduce random combinatorics, parent particles were selected if the calculated invariant mass fell within 3σ around the peak after background subtraction. The data were corrected, as a function of p_T, for efficiency and detector acceptance. Monte Carlo studies showed that the corrections were constant as a function of rapidity over the measured regions. Further details of these reconstruction and correction techniques can be found in Refs. [5,10] and references therein. Several contributions to the systematic uncertainty of particle yields were studied: detector simulation and efficiency calculations, inhomogeneities of the detector responses, pileup effects, and the extrapolation of the data fits to zero p_T. In $p+p$ collisions, an additional normalization error due to varying beam luminosity and trigger efficiencies of $\sim$4% is included. The Λ yields were corrected for feed-down from multistrange baryons using the measured spectra, the correction was of the order of 15%.

III. RESULTS

A. Yield enhancement factors

For each species i, the yield enhancement, $E(i)$, above that expected from $\langle N_{\mathrm{part}} \rangle$ scaling was calculated using

$$E(i) = \frac{\mathrm{Yield}^{AA}(i)\langle N_{\mathrm{part}}^{NN} \rangle}{\mathrm{Yield}^{NN}(i)\langle N_{\mathrm{part}}^{AA} \rangle}. \qquad (1)$$

Figure 1 shows $E(i)$ as a function of $\langle N_{\mathrm{part}} \rangle$; the inclusive proton data illustrate the effects for nonstrange baryons [13]. Midrapidity hyperon yields measured as a function of centrality in Au+Au [5] and $p+p$ [10] collisions were used. The number of participants $\langle N_{\mathrm{part}} \rangle$ and the number of binary collisions $\langle N_{\mathrm{bin}} \rangle$ were estimated via a Monte Carlo Glauber calculation [14,15]. Since the $p+p$ data were recorded with a trigger that was only sensitive to the non-singly diffractive (NSD) part of the total inelastic cross section, all $p+p$ yields have been corrected by $\sigma_{\mathrm{NSD}}^{NN}/\sigma_{\mathrm{inel}}^{NN}(=30/42)$ to obtain the total invariant cross sections.

It can be seen that there is an enhancement in the yields over that expected from $\langle N_{\mathrm{part}} \rangle$ scaling for all the particles presented. Since the proton yields are not corrected for feed-down, which is predominantly from the Λ and Σ, the p measurement is actually a sum of the primary protons and those from secondary decays. The integrated $\Lambda + \Sigma^0$
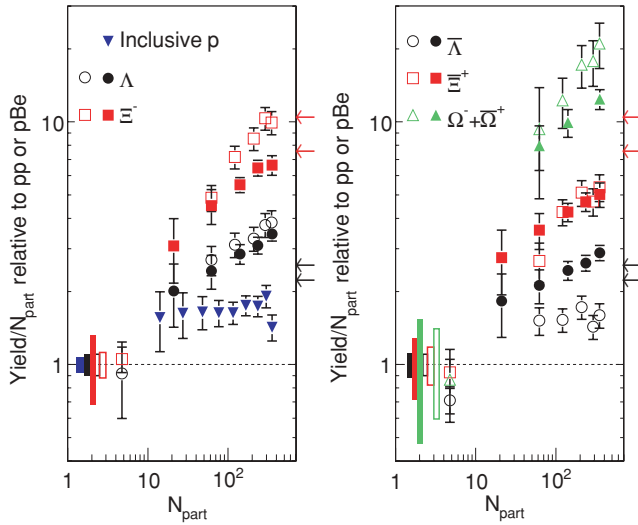
FIG. 1. (Color online) Midrapidity $E(i)$ as a function of $\langle N_{\text{part}} \rangle$ for Λ, $\bar{\Lambda}$ ($|y| < 1.0$), Ξ^-, $\overline{\Xi}^+$, $\Omega^- + \overline{\Omega}^+$ ($|y| < 0.75$), and inclusive p ($|y| < 0.5$). Boxes at unity show statistical and systematic uncertainties combined in the $p+p$ ($p+$Be) data. Error bars on the data points represent those from the heavy ions. The solid markers are for Au+Au at $\sqrt{s_{NN}} = 200$ GeV and the open symbols for Pb+Pb ($|y| < 0.5$) at $\sqrt{s_{NN}} = 17.3$ GeV [4]. The arrows on the right axes mark the predictions from a GC formalism model when varying T from 165 MeV [$E(\Xi^-) = 10.7$, $E(\Lambda) = 2.6$] to 170 MeV [$E(\Xi^-) = 7.5$, $E(\Lambda) = 2.2$]. The red arrows indicate the predictions for Ξ and the black arrows those for Λ, see text for details [12].

over the inclusive p ratio varies from 30% to 40% for the $p+p$ and Au+Au collisions, respectively. If only primary protons were measured, then E(proton) would be closer to unity. A hierarchy in the scale of enhancements, which grows with increased strangeness of the baryon, is observed. This trend is predicted by grand canonical (GC) ensemble approaches, as is the fact that the $E(i)$ values for each baryon/antibaryon pair are similar in shape [2]. The difference in the scale of the enhancements for baryon and antibaryon, especially at the SPS, is due to the existence of a nonzero net-baryon number. However, the ratio of E(antibaryon) to E(baryon) varies as a function of $\langle N_{\text{part}} \rangle$ at the SPS, possibly signifying different production/annihilation mechanisms for (anti)particles at the SPS compared to those at RHIC. For instance, the net-Λ yields at the SPS can be successfully described via multiple interactions of the projectile nuclei [16]. This effect is expected to be less significant at RHIC. It is also interesting to note that the measured enhancements for the Λ, anti(Ξ), and Ω at RHIC are the same, within errors, as those calculated from the midrapidity SPS data (open symbols in Fig. 1) despite an order of magnitude increase in the collision energies. Theoretical predictions using the GC ensemble approach predict a significant decrease in all the (anti)baryon enhancements with collision energy [2]. A GC model, with a chemical freeze-out temperature of $T = 165$ MeV and a baryon chemical potential $\mu_b = 29$ MeV, calculates enhancements of $E(\Xi^-) = 10.7$ and $E(\Lambda) = 2.6$ for the most central Au+Au events at $\sqrt{s_{NN}} = 200$ GeV [12]. These enhancement calculations cannot consistently describe

the (anti)Ξ and the (anti)Λ enhancements. However, the scales of the enhancements are very sensitive to the assumed freeze-out temperature, and if $T = 170$ MeV is used, then $E(\Xi^-) = 7.5$ and $E(\Lambda) = 2.2$.

Whereas the measured enhancements are approximately constant for the inclusive protons, they are clearly not for the Λ, Ξ, and Ω; this is again counter to theoretical expectations, in which the dependence of the strange baryon yields is expected to be linear with $\langle N_{\text{part}} \rangle$ for $\langle N_{\text{part}} \rangle \gtrsim 20$. One explanation for this deviation from theory is that the volume responsible for strangeness production is not linearly proportional to the geometrical overlap region, as assumed in the model. A model that gives a reasonable description of the magnitudes and shapes of the enhancements with respect to centrality is described in Ref. [17]. This model allows for an oversaturation of strange quarks, which varies with centrality, and thus does not invoke chemical equilibrium.

B. Nuclear modification factors

Figure 1 is an average measurement of the difference in production between nucleus-nucleus and nucleon-nucleon collisions. Since the p_T distributions of the particles are approximately exponential, these results are dominated by the physics occurring at $p_T \lesssim 2$ GeV/c. Differences in the p_T distributions for $p+p$ and Au+Au data are studied by calculating the nuclear modification factor, i.e.,

$$R_{\text{AA}}(p_T, i) = \frac{d^2 N^{\text{AA}}(i)/dp_T \, dy}{T_{\text{AA}} \, d^2 \sigma^{NN}(i)/dp_T \, dy}, \quad (2)$$

where $T_{\text{AA}} = \langle N_{\text{bin}} \rangle / \sigma_{\text{inel}}^{NN}$. Figure 2(a) shows R_{AA} for Λ and the sum $\Xi + \bar{\Xi}$ for 0–5% Au+Au collisions along with those for inclusive $p + \bar{p}$ measurements [18,19].

A striking feature of Fig. 2 is that both the central (top panel) and peripheral (bottom panel) R_{AA} distributions for the Λ and $\Xi^- + \overline{\Xi}^+$ reach maxima that are much greater than unity, a value that would signify binary collision scaling. In fact, the peripheral collision R_{AA} distributions for the hyperons, Fig. 2(b), are of approximately the same magnitude as the central R_{AA} data, Fig. 2(a), at intermediate to high p_T. These results are in contrast to the earlier reported suppression of high p_T hyperons observed via the binary scaled ratio of central to peripheral events, R_{CP} [5,19–21]; these data are reproduced in Fig. 3.

$$R_{\text{CP}}(p_T, i) = \frac{[d^2 N^{\text{cent}}(i)/dp_T \, dy]/\langle N_{\text{bin}}^{\text{cent}} \rangle}{[d^2 N^{\text{periph}}(i)/dp_T \, dy]/\langle N_{\text{bin}}^{\text{periph}} \rangle}, \quad (3)$$

Nonstrange hadrons reveal a similar suppression when using $p+p$ or peripheral Au+Au collisions as a reference. For $p_T > 1.5$ GeV/c, unidentified charged hadrons show a suppression of the Au+Au spectra [7]. Comparing R_{AA}, Fig. 2, to R_{CP}, Fig. 3, shows that $R_{\text{AA}}(\Lambda) \approx R_{\text{AA}}(\Xi) \neq R_{\text{AA}}(p)$ but that $R_{\text{CP}}(\Lambda) \approx R_{\text{CP}}(\Xi) \approx R_{\text{CP}}(p)$, especially at intermediate to high p_T. This is possibly due to phase-space effects in the $p+p$ data extending to this intermediate p_T regime. It is surprising that this decreased production in $p+p$ events, while predicted in the soft physics/thermal production regime, i.e., $p_T < 2$ GeV/c, extends out to, and even dominates in,
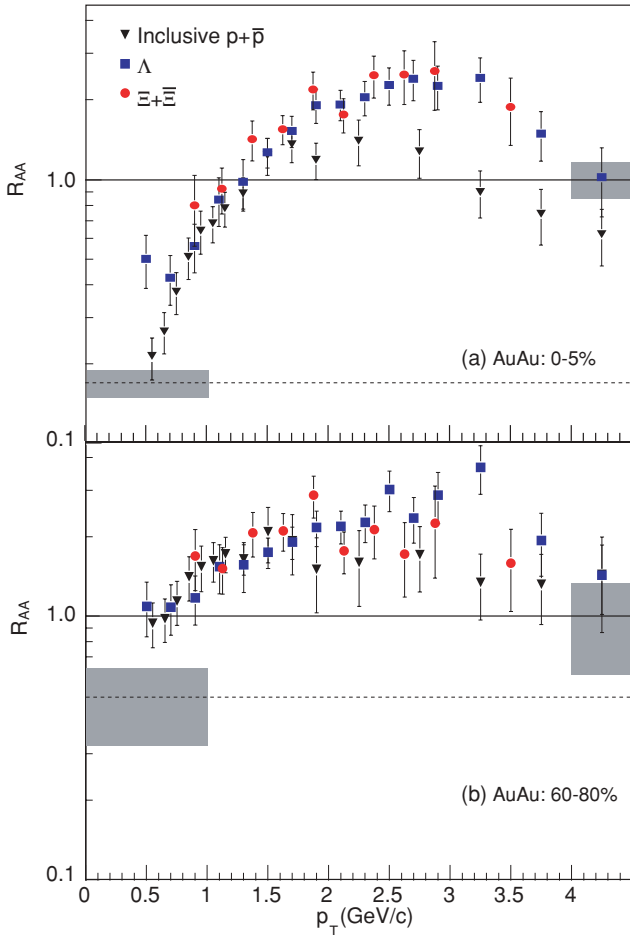
FIG. 2. (Color online) R_{AA} from (a) 0–5% and (b) 60–80% central Au+Au events for $p+\bar{p}$ [18,19], Λ, and $\Xi^- + \overline{\Xi}^+$. Errors shown are statistical plus systematic added in quadrature. The band at unity shows the systematic uncertainty on $\langle N_{bin} \rangle$. The dashed line below unity shows the expected value of R_{AA} should the yields scale with $\langle N_{part} \rangle$, and the band around it shows the systematic uncertainty on $\langle N_{part} \rangle$.

FIG. 3. (Color online) R_{CP} Au+Au events for $p+\bar{p}(0-12\%/60-80\%)$ [19], and $\Lambda + \bar{\Lambda}$ and $\Xi^- + \overline{\Xi}^+$ (0–5%/60–80%) [5]. Also shown as the dashed curve are the results for $4h^+ + h^-$ for 0–5%/60–80% [20]. Errors shown are statistical plus systematic added in quadrature. The band at unity shows the systematic uncertainty on $\langle N_{bin} \rangle$. The dashed line below unity shows the expected value of R_{CP} should the yields scale with $\langle N_{part} \rangle$, and the band around it shows the systematic uncertainty on $\langle N_{part} \rangle$.

this intermediate p_T region. Figure 2(a) suggests that this effect is strong out to $p_T \sim 3$ GeV/c. The shapes of the R_{CP} distributions at intermediate to high p_T are generally interpreted as the result of parton energy loss in the hot dense matter and quark coalescence during hadronization. A comparison of Figs. 2(a) and 2(b) shows that the turnover points occur at approximately the same p_T. These data suggest that an enhancement of strangeness production has already set in in peripheral Au+Au collisions. This behavior is similar to that observed for the total yields in Fig. 1 and quantitatively consistent with expectations from canonical suppression in $p+p$. Some portion of the R_{AA} peak may be explained via the Cronin effect, the observed increase in intermediate p_T spectra in p-A collisions [22]. However, the Cronin enhancement stays constant, or possibly increases, as a function of centrality [23], and this is not seen in our data. Effects due to radial flow in the Au+Au data are significant at RHIC energies, even for the multistrange baryons [24], but flow dominates only at low p_T. The shapes of the R_{AA} distributions below 1 GeV/c
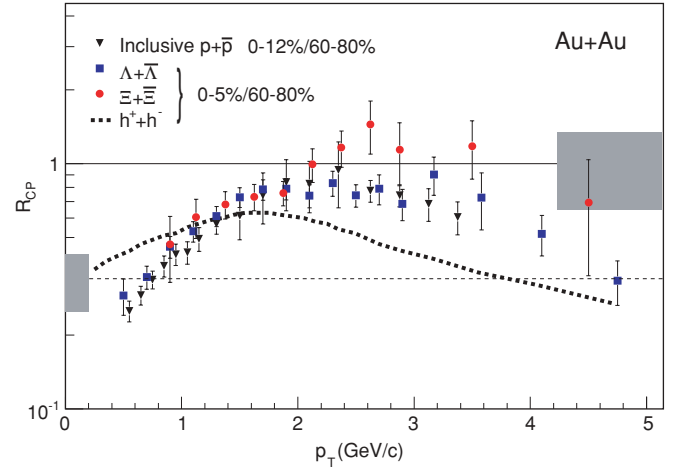
are markedly different. The peripheral collision data indicate approximate binary scaling of the baryon yields, while the most central data fall beneath binary scaling but significantly above that suggesting participant scaling. This again indicates that there are different constraints on baryon production when going from $p+p$ to peripheral to central Au+Au collisions.

C. Comparison to models

Comparisons to dynamical models can be used to understand in more detail how the close-to-equilibrium strangeness production can be achieved and whether the same mechanisms affect strange particle production at intermediate p_T. In the HIJING model [25,26], the yields and qualitative features of the strange baryon R_{AA} measurements (solid curves in Fig. 4) can only be obtained when baryon junctions and color strings are included [26,27]. EPOS calculations [28,29] (dashed curves in Fig. 4) produce similarly large differences in the hyperon R_{AA} and R_{CP} [28] to those measured at RHIC and also give a qualitatively reasonable representation of the shape of the data. EPOS describes particle production via a parton model in which Au+Au collisions are represented as many binary interactions. Each binary interaction is described by a longitudinal color field that is expressed as a relativistic string, or parton ladder. At a very early proper time, before hadronization, the collision region is split into two environments: the core, in which the density of strings is high, and the corona, which surrounds the core and has a low string density. Production from the corona is due to collisions of nucleons at the periphery of the nuclei and modeled via string fragmentation. Corona production is thus similar to that from $p+p$ collisions. Meanwhile particle production from the core is approximated via a simple statistical hadronization process,
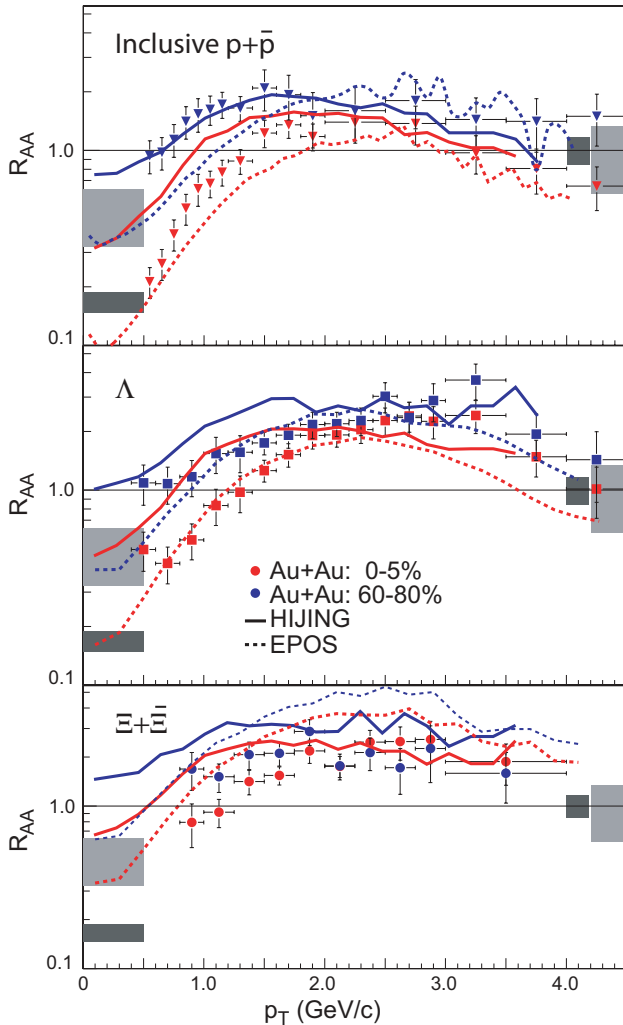
FIG. 4. (Color online) Comparison of R_{AA} from data to HIJING [26] and EPOS [29] for 0–5% and 60–80% most central Au+Au collisions, for $p + \bar{p}$, Λ, and $\Xi^- + \overline{\Xi}^+$. Errors shown are statistical plus systematic added in quadrature. The bands at unity shows the systematical uncertainty on $\langle N_{bin} \rangle$. The bands below unity on the left of the graphs are centered at the expected value of R_{AA} should the yields scale with $\langle N_{part} \rangle$, and the widths of the bands indicate the systematic uncertainty on $\langle N_{part} \rangle$.

similar to that described in Ref. [30], a collective flow profile is then imposed upon these particles. The relative weight of

core to corona production varies with both centrality and particle species, with the core dominating production in the most central events. Strange baryons are dominated by core production even in peripheral events.

IV. SUMMARY AND CONCLUSIONS

In summary, we observe enhanced strange baryon midrapidity production in Au+Au collisions, especially in the more central events, when compared to the $\langle N_{part} \rangle$ scaled $p + p$ data from the same energy. The measured yields fail to scale with $\langle N_{part} \rangle$ as predicted if the GC regime is reached and the particle production volume scales with the geometrical overlap region. The magnitudes of the suppressions are different to those predicted but close to those measured at SPS energies. At intermediate p_T, the R_{AA} values are higher than binary scaling of $p + p$ data would predict. When attempting to understand the evolution of strange particle production from $p + p$ to central Au+Au, one must take into account both the effects due to a suppression of strangeness production in $p + p$ and jet quenching plus quark recombination in Au+Au collisions, with the former dominating at intermediate p_T. Since the measured R_{CP} values for all strange baryons are equal to those of the inclusive protons in the intermediate and high p_T regions and are significantly below binary scaling, the $p + p$-like suppression is already predominantly removed in peripheral Au+Au collisions.

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