Reconstructing $\Sigma^0$ decays in STAR

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Abstract. Typical comparisons of data from nuclear collisions to particle production models require a caveat for (anti)Λ yields from experimental inability to separate the contributions of those yields from Σ state decays. Recent analysis in STAR is leading toward resolving the contribution from excited Σ states [1], but the bulk contribution comes from electromagnetic decays of the (anti)Σ^0.

In the STAR detector, photon conversions into $e^+e^-$ pairs in the detector material have been used to identify photons from π^0 decays [2]. A similar technique has been used here to identify photons from (anti)Σ^0 decays in conjunction with STAR’s excellent PID capabilities for finding the associated (anti)Λ daughters. We report here on progress toward measuring the (anti)Σ^0 yields in various nuclear collisions at RHIC.

1. Introduction

Reasons to understand the production of Σ states are various, but generally stem from their decay contributions to other baryon states. A primary example of this is the contribution of the $\Sigma^0$ to the Λ yields and spectra via its electromagnetic decay $\Sigma^0 \rightarrow \Lambda\gamma$ (with a branching ratio close to 100%). Because the decay is electromagnetic, the short decay lengths make this measurement possible only by identification of the partner γ, a task few detectors are designed to handle well.

Awareness of such contributions may be necessary to make accurate comparisons with particle production models of nuclear collisions. A notable instance involves one of the more prominent expectations of quark gluon plasma: strangeness enhancement in the antihyperon channel measured via $\bar{\Lambda}/\bar{p}$ [3]. Aside from correcting for feeddown from $\bar{\Lambda}$, $\Xi$, and $\Omega$ decays, and even assuming the measured $\bar{\Lambda}$ yield is inclusive of the $\Sigma^0$ yield, the observed $\bar{p}$ yield is still influenced by $\Sigma^-$ decays. Without knowledge of the Σ states’ yields, unproven model assumptions must be used to correct for their contributions, leading to possibly premature conclusions.

‡ For the full author list and acknowledgements, see Appendix ”Collaborations” in this volume.
Another example of where ignorance of $\Sigma$ production may affect physics interpretation is in the spectra of the $\Lambda$. Such spectra are often used in diagnoses of radial flow in heavy ion collisions through $\langle p_T \rangle$ or inverse slope determinations, but certainly include the products of the $\Sigma^0$ decay (even though the electromagnetic and weak decay lifetimes of the $\Sigma^0$ and $\Sigma^\pm$ respectively exclude their decay during any reasonable lifetime expectations of the fireball). It is unknown whether final state interactions of the $\Sigma$ states are equivalent to that of the $\Lambda$ (one expects at least a small change from their mass difference in the view of ideal flow) as interaction cross sections with other species have been scarcely measured (total cross sections of $\Sigma^-$ and $\Lambda$ with protons have been measured with a very small region of overlap at $\sqrt{s} \approx 15$ GeV, where they appear to agree with a value of approximately 33 mb \cite{4}). Additionally, there exist data from only one experiment on how the production of $\Sigma^0$ and $\Lambda$ differ over phase space in nuclear collisions ($p+Be$ at $p_{lab} = 28.5$ GeV/c), from which it appears that the ratio $\Lambda_{\Sigma^0 \rightarrow \Lambda}/\Lambda_{\text{inclusive}}$ is relatively constant at approximately 1/4. \cite{5}. However, with possibly different feeddown contributions from resonance states in larger colliding systems, that may not be true in heavy ion collisions.

The latter point also has bearing on whether trends observed in the data are coincidental. Of note, a linearity between $\Lambda$ yields and $h^-$ was seen in 130 GeV $Au+Au$ data at RHIC \cite{6}. If the factors that make up this $\Lambda$ measurement do not scale, we may be fooled.

### 1.1. $\Sigma^0/\Lambda$

From the above arguments, it is evident that a measurement of the relative yields of the $\Sigma^0$ and $\Lambda$ would prove useful at RHIC. It has been stated that isospin dictates the ratio of the production cross sections $\sigma(\Sigma^0)/\sigma(\Lambda)$ should be 1/3 \cite{7}. Reasons for this are not obvious, so we will examine other production arguments here. To be clear, we will henceforth focus on such yields after strong (resonance) decays, but before electroweak decays.

#### 1.1.1. Thermal Models

For thermal models, one needs to establish the parameters of the model to use for determining a ratio. A good example is the set from a fit to central 200 GeV $Au+Au$ data from STAR \cite{8}. Using these parameters as input to the THERMUS thermal model \cite{9}, one obtains for the primordial ratio a value of 0.67, and for the ratio after resonance decay contributions a value of 0.36. The dependence of either of these values on the parameters of the thermal model is very weak, but it is clear that the resonances play a strong role. This is noteworthy because there are indications that these resonances are under-populated relative to the thermal model in the $Au+Au$ data, but are reasonable in $p+p$ \cite{8,10}. So reality may be somewhere between the two values if the thermal predictions are correct.
1.1.2. Quark Coalescence Models  Simple counting rules in quark coalescence models, expected to be relevant only under conditions of very dense matter with partonic degrees of freedom [11, 12], lead to yield ratios of 1/1 for primordial production, but feeddown from resonances into both species reduces this ratio to 1/5 if the resonances are fully-populated [13]. Again, reality may be somewhere in the middle, but the window is larger than for the thermal model. If central $Au+Au$ collisions produce a $\Sigma^0/\Lambda$ value near 0.2 or 1.0, this may serve as an indicator for quark coalescence.

1.1.3. Event Generators  As one example of an event generator, HIJING/B$\overline{B}$ has no final state rescattering to alter yields of resonances [14]. It predicts a value of 0.37 for the ratio in 200 GeV $d+Au$ collisions, which agrees with the thermal model prediction for a fully equilibrated system at RHIC, including resonances.

1.1.4. Past Results  The energy threshold for producing a $\Sigma^0$ (via associated production, $p+p \rightarrow pK^+\Sigma^0$) is slightly higher than that for creating a $\Lambda$ ($p+p \rightarrow pK^+\Lambda$), so the initial behavior at low energy is dominated by that of the threshold for $\Sigma^0$ production, as shown in Fig. [11] Further details of production (and of the rise in the $\Sigma^0/\Lambda$ ratio) at these low energies appear to be well-understood [16]. This is followed perhaps by fluctuations in the ratio when the thresholds for $\Lambda\overline{\Lambda}$ and $\Sigma^0\Sigma^0$ pair production are reached, but there is little data in this range to clarify this.

The expectation is that the data then approach the "ideal" ratio of 1/3 from isospin as the available energy for production rises well above thresholds. For the most part,
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![Figure 2. Contour plot of Armenteros-Podolanski decay variables $p_T^{AP}$ versus $\alpha^{AP}$ from $V_0$ decays in the STAR detector. Notable features include combinatoric background in the center, a $K^0_{\text{short}}$ arc across the top, (anti)$\Lambda$ arcs on the sides, and a $\gamma$ conversion band along the bottom at low $p_T^{AP}$.](image)

this seems to be approximately true, though only one data point exists from a colliding system larger than $p+Be$, from $p+Ne$ at $\sqrt{s_{NN}} = 24$ GeV [17]. This point has a rather high value of $0.75 \pm 0.45$, but is consistent with $1/3$ within its errors. This is insufficient to conclude whether larger colliding systems behave differently. At higher energies, there exist only the measurements of $Z^0$ decay products [18], and nothing from hadronic interactions.

2. Experiment

2.1. Technique

In order to observe the charged $\Sigma$ states in an experiment, it is important to have either good $\pi^0$ or neutron detection efficiency. The STAR detector has not had strong capabilities in these areas, though a measurement has been made of the $\pi^0$ spectrum using the STAR TPC detector in 130 GeV $Au+Au$ collisions [2]. It may also be possible to use the now-operational STAR electromagnetic calorimeters to identify $\pi^0$ candidates for (anti)$\Sigma^+$ decays [19].

The STAR TPC $\pi^0$ measurement took advantage of photon conversions ($\gamma \rightarrow e^+e^-$) in detector material to observe the 4-body final state $\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-e^+e^-$. While the combinatorics of the technique leave the background under the $\pi^0$ mass peak too large for identifying individual pions, the reconstructed photons do have enough signal-to-noise to use in combination with other potential decay products (as demonstrated by the $\pi^0$ measurement). This, along with strong $\Lambda$ identification capabilities, is what makes $\Sigma^0$ decay observation possible in STAR.
In the current $\Sigma^0$ analysis, a different $\gamma$-finder was used from that of the $\pi^0$ analysis. It turns out that a photon conversion has all the characteristics of the $V^0$ decays used in weak decay analyses in STAR: two oppositely charged particles originating from a displaced vertex (several centimeters or more) with a reconstructed parent originating from the primary collision vertex. However, two aspects uniquely identify these $V^0$s: their daughters have $dE/dx$ characteristics of electrons, and they occupy a unique region of the Armenteros-Podolanski decay variable $p^A_T$ (shown in Fig. 2). Because the electron $dE/dx$ band crosses other $dE/dx$ bands in the range of interest (low momentum), a simple cut on low $p^A_T$ is the most stringent. The conversions are most likely to occur in detector material, so the locations of the $\gamma$ candidates’ decay vertices clearly reveal the structure of the STAR apparatus [20], as can be seen in Fig. 3.

2.2. Data

The combinatoric background in 200 GeV $Au+Au$ collisions has proven to be too difficult to overcome using this reconstruction technique, and no clear signal has been seen. While this is not an issue in $p+p$ data in STAR, the accumulated statistics are too few to perform an analysis.

The STAR data collected from minimum bias 200 GeV $d+Au$ collisions, however, benefit from both low combinatoric backgrounds, and significant statistics. From 14.7 million minimum bias events, one can see clear evidence of the $\Sigma^0$ signal as shown in Fig. 4 for rapidities between $\pm 0.75$ over all $p_T$.

To measure a yield, it is necessary to understand the background under the invariant mass peaks. For this purpose, an approximation of the background shape is determined by rotations of the $\Lambda$ and $\gamma$ candidates with respect to each other in azimuth (about the beam axis). This technique ensures that any possible event classes (such as number of binary collisions) are appropriately represented. Within the errors of the data points, the approximation appears roughly consistent when scaled to match the data away from the invariant mass region of interest. This provides confidence that one can fit the shape of the background from the approximation, and include some representation of the signal on top of it. Varying the fit functions and ranges gives a systematic error, but the statistical errors of the measurements dominate. The resulting reconstructed
counts from four $p_T$ bins of $\Sigma^0 + \Sigma^0$ are shown in Fig. 5. Using the uncorrected counts over all $p_T$ we find $\Sigma^0 / \Sigma^0 = 0.6 \pm 0.3$.

2.3. Corrections

Efficiency corrections for this $\Sigma^0$ analysis are difficult to certify. Statistics under the invariant mass peak are so few that comparisons cannot be made between real and simulated data for distributions used for cuts. Rather than tackle this issue, the analysis
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is presently being modified to use the same $\gamma$-finder which was used in the $\pi^0$ analysis, which has shown increased efficiencies for identifying $\gamma$ candidates from $\pi^0$ decays over simply selecting $V^0$ candidates with low $p_T^{AP}$. Efficiencies and yields from the modified analysis are expected in the future.

The experimentally measurable $\Sigma^0$ yield suffers from only minor feeddown corrections. From weak decays, contributions include $\Xi^0$ decays with a branching ratio of $(3.33 \pm 0.10) \times 10^{-3}$, and $\Xi^-$ decays with branching ratios below $10^{-3}$. Even if $\Xi$ yields were similar to that of the $\Lambda$, the feeddown to $\Sigma^0$ would be small. Geometric cuts on the $\Sigma^0$ originating from the collision vertex also cut mildly into the efficiency for reconstruction of these secondary $\Sigma^0$ candidates.

Strong decays into the $\Sigma^0$ include a $12 \pm 2\%$ branching ratio from $\Sigma(1385)$ decays and undetermined fractions of other, heavier excited $\Sigma$ states. Excited $\Lambda$ states can also play a role with 100% and 40% of $\Lambda(1405)$ and $\Lambda(1520)$ decaying into $\Sigma\pi$, respectively, and uncertain fractions of higher mass states. But the expectedly lower yields of all such excited states implies only small contributions from the lightest of these. Measurements of the $\Sigma(1385)$ yield in high energy nuclear collisions by STAR \cite{1} will likely aid our understanding of possible resonance feeddown corrections.

3. Summary

We have observed a signal for (anti)$\Sigma^0$ in STAR for minimum bias 200 GeV $d+Au$ collisions at midrapidity using a 4-body final state reconstruction. While the signal is not strong, there is hope for improvement via a different $\gamma$-finder which has shown higher efficiencies in other STAR analyses, such that a yield can be measured. Finding yields in other colliding systems may also be possible with further data acquired by STAR: improved statistics of 200 GeV $Au+Au$ data from 2004 may overcome the large combinatorial background in that data; 62 GeV $Au+Au$ data taken in 2004 is expected to have reduced combinatorial background, as should $Cu+Cu$ data to be taken in 2005; and future $p+p$ runs should provide sufficient statistics to observe the (anti)$\Sigma^0$ signals.

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