The longitudinal polarization of hyperons in the forward region in polarized \(pp\) collisions

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We study the longitudinal polarization of hyperons and anti-hyperons at forward pseudorapidity, \(2.5 < \eta < 4\), in singly polarized \(pp\) collisions at RHIC energies by using different parameterizations of the polarized parton densities and different models for the polarized fragmentation functions. The results show that the \(\Sigma^+\) polarization is able to distinguish different pictures on spin transfer in high energy fragmentation processes; and the polarization of \(\Lambda\) and \(\bar{\Lambda}\) hyperons can provide sensitivity to the helicity distribution of strange sea quarks. The influence from beam remnant to hyperon polarization in the forward region is also discussed.

PACS numbers: 13.88.+e, 13.85.Ni, 13.87.Fh

The polarizations of hyperons and anti-hyperons in polarized proton-proton (\(pp\)) collisions have attracted much attention recently, as they provide accesses to different aspects of spin physics \[1\,2\,3\,4\,5\,6\,7\,8\]. The running of high energy polarized \(pp\) collider at RHIC provides a good opportunity for these studies \[1\]. The available experimental and theoretical studies mostly focused on mid-rapidity region with high transverse momentum \(p_T\) \[2\,3\,5\,6\]. Phenomenological study in this region showed that \(\Lambda, \Sigma\) hyperon production at high \(p_T\) are dominated by quark fragmentation, and their polarizations can be used to study the polarized fragmentation functions \[3\,6\,7\]. On the other hand, the polarizations of \(\Lambda\) and other anti-hyperons, can provide sensitivity to polarized parton distribution functions, in particular to those for the sea quark and anti-quark \[7\,8\]. Similar conclusion was also obtained for hyperons polarization in semi-inclusive deep inelastic scattering \[8\,10\]. First measurement on longitudinal polarization of \(\Lambda\) and \(\bar{\Lambda}\) in \(pp\) collisions has been made in mid-rapidity at \(\sqrt{s} = 200\) GeV by the STAR experiment at RHIC at intermediate \(p_T\) recently \[9\]. The experimental uncertainties are still statistics limited, and may be improved in future measurement. It is interesting that the STAR experiment is proposing a detector upgrade in the near future, which may enable hyperon polarization measurement in the forward range of \(pp\) collisions \[11\]. Compared with hyperons at mid-rapidity, the forward hyperons carry larger momentum fraction of the beam and their polarizations may have different properties. Therefore, it is of practical importance to see the behaviors of hyperon polarization in this kinematic region and this short note aims to make such an analysis. We extend our calculations on hyperon polarization at mid-rapidity in \(pp\) collisions to large rapidity region, and the results may serve as a guide for future experimental study.

We consider the inclusive production of hyperons \(H\) in \(pp\) collisions with one beam longitudinally polarized, where the polarization of hyperons is defined as,

\[
P_H = \frac{d\sigma_{p_p-H+X} - d\sigma_{p_p-H-X}}{d\sigma_{p_p-H+X} + d\sigma_{p_p-H-X}} = \frac{d\Delta \sigma}{d\sigma},
\]

where the subscripts + and − denote positive and negative helicity, and \(d\sigma\) and \(d\sigma\) are the polarized and unpolarized inclusive production cross sections. Recently, the STAR experiment has measured the \(\Lambda (\bar{\Lambda})\) production cross section in \(pp\) collision with \(p_T\) up to 5 GeV at \(\sqrt{s} = 200\) GeV, which is in agreement with pQCD calculation under factorization framework \[12\]. Similarly, the polarized cross section in Eq.(1) can be described by convolution of polarized parton distribution and fragmentation functions, and the polarized cross section of partonic scattering which is calculable in pQCD. The hyperon polarization in \(pp\) collision thus provide connection to the polarized parton distribution and fragmentation functions. The polarized parton distribution function can be in general obtained by global parameterization of polarized data in different reactions, though large uncertainties still exist especially for gluon and sea quarks due to the lack of abundant data \[12\].

On the polarized fragmentation function, there are mainly two approaches in literature. Similar as the (polarized) parton distribution function, one can make a global parameterization \[5\]. However, the available data are still far from being abundant enough to give solid constraint. At this stage, some key features still rely on phenomenological models \[13\,14\,15\]. In this analysis, we model the polarized fragmentation function according to the origins of hyperon. The calculation method of hyperon polarization with this model has been applied to the studies of hyperons and anti-hyperons polarization in \(e^+e^-\) \[13\,15\], in polarized lepton-nucleon scattering \[21\,22\] and also in polarized \(pp\) collisions \[3\,8\]. The detailed description for the case of \(pp\) collisions can be found in Ref. \[8\]. In the following part of this paper, we first briefly summarize the main points on the calculation procedure of hyperon polarization in \(pp\) collisions and then give the results.

In our analysis, the Lund string fragmentation model \[23\] is used for the fragmentation process, which enables us to distinguish between \(H\) that contain the fragmenting parton and those that do not. Those di-
rectly produced hyperons that contain the fragmenting parton can be polarized, and the relation between hyperon polarization and the polarization of fragmenting parton is described with two pictures of hyperon spin content, which are obtained from the SU(6) wave function or polarized deep-inelastic lepton-nucleon scattering data (DIS). Those hyperons that do not contain the fragmenting parton are not polarized. This model can also distinguish between directly produced \( H \) and \( H \) which are decay products of heavier resonances. The spin transfer in the decay process is also considered \([13,14]\). One advantage of this model is that the main feature of hyperon polarization is determined by the relative contribution of different classes based on the origins, which is independent of polarization property.

In our calculation of hyperon polarization, we have used the PYTHIA event generator for the unpolarized hyperon production in \( pp \) collision (see detailed description in Sec.IIC of Ref. [8]). PYTHIA incorporates the hard scattering processes and uses the Lund string fragmentation model \([22]\), which has been commonly used for hadron-hadron collisions and its output has been tested and tuned to describe a vast body of data.

We first look into the different fractional contributions from the fragmentation of different quark flavors and gluon, which are expected to play different roles in hyperon’s polarization. These contributions are independent of polarization property and have been determined by large amount of data collected over the past years. They are thus considered to be well-modeled in Monte-Carlo event generators like PYTHIA. We have used PYTHIA6.420 \([23]\) in its default tune to estimate these contributions. We note that the recent data on \( \Lambda(\bar{\Lambda}) \) production at RHIC in \( pp \) collisions at \( \sqrt{s} = 200 \) GeV can also be described by PYTHIA with certain \( K \) factor \([12]\), which does not affect the relative fractions here and thus the corresponding hyperon polarization shown later.

![FIG. 1: Contributions to \( \Sigma^+(uds) \) production with \( p_T \geq 3 \) GeV in \( pp \) collisions at \( \sqrt{s} = 500 \) GeV versus \( \eta \).](image1)

![FIG. 2: Contributions to \( \Lambda(uds) \) production with \( p_T \geq 3 \) GeV in \( pp \) collisions at \( \sqrt{s} = 500 \) GeV versus \( \eta \).](image2)

Figure 1 shows the results of the fractional contributions to \( \Sigma^+ \) production from the fragmentation of antiquarks/quarks of different flavors and of gluons in \( pp \) collisions versus pseudorapidity \( \eta \) at \( \sqrt{s} = 500 \) GeV for hyperon transverse momenta \( p_T > 3 \) GeV. We see that, \( \Sigma^+ \) production at large \( \eta \) is dominated by \( u \) quark fragmentation. Most of them are directly produced and contain the fragmenting \( u \) quark (denoted as “direct 1st rank” in Fig.1), whose percentage reaches 80% at \(|\eta| = 4\). The contribution from gluon is very small at \(|\eta| > 2.5\). Most of \( \Sigma^+ \)’s from gluon are directly produced and apparently don’t contain the fragmenting gluon (denoted as “direct 2nd rank” in Fig.1). The decay contribution from heavier hyperons (denoted as “decay” in Fig.1) is very small in the whole \( \eta \) region. The contributions from sea quarks are negligible as expected. In the large \( \eta \) region, we can also see the contribution of beam remnant, as seen in Fig. 1(h). As \( u \) quark carries most of \( \Sigma^+ \)’s spin either in SU(6) or DIS picture, we expect \( \Sigma^+ \)’s polarization be sizable and increase with \( \eta \).

The fractional contributions for \( \Lambda \) production with \( p_T > 3 \) GeV at \( \sqrt{s} = 500 \) GeV are shown in Fig. 2. Comparing with the results of \( \Sigma^+ \), the situation for \( \Lambda \) is more complicated. The largest contribution comes from \( u \) quark’s fragmentation in the forward region of \( 2.5 < \eta < 4 \), but most of them are from decay contribution. The shape of \( d \) quark’s contribution is similar as that of \( u \) quark, but the size is about one half. The contribution from decays of heavier hyperons is sizable for each flavor in the whole \( \eta \) region. The contribution of \( s \) quark is a few percent in the forward region, and thus \( \Lambda \) polarization is expected to be small as \( u \) or \( d \) quark does not carry \( \Lambda \)’s spin in SU(6) picture or carries only a small fraction in DIS picture. At \( \eta \approx 4 \), the contribution of beam remnant is also seen as \( \Sigma^+ \)’s case.

Figure 3 shows the evaluated polarization results for the \( \Lambda, \Sigma^+ , \Sigma^- , \Xi^0 \) and \( \Xi^- \) hyperons as a function of pseudorapidity \( \eta \) for \( p_T > 3 \) GeV at \( \sqrt{s} = 500 \) GeV using different parameterizations for the polarized parton dis-
contributions and using the SU(6) and DIS pictures for the spin transfer factors in the fragmentation. To be consistent with our model on polarized fragmentation process, the polarized partonic cross section is evaluated at leading order (LO) [24] and LO sets of polarized parton distribution functions are used. Here we pick two LO sets of GRSV00 parameterization for the polarized parton distribution functions, to study the sensitivity of hyperon polarization to strange sea quark helicity distributions, as the main difference between these two sets is on the sea quarks [22]. The main characteristics of the polarization results in the forward region of $2.5 < \eta < 4$ are:

- The magnitudes of $\Sigma^+$, $\Sigma^-$ polarization are much larger than those for the $\Lambda$, $\Xi^0$ and $\Xi^-$ hyperons because of the dominant contributions of the valence quarks ($u$ and $d$) in their productions. The $\Sigma^+$ polarization increases with $\eta$ and is larger than 0.3 at $\eta \approx 4.0$ with the SU(6) picture. We take into account the contribution of beam remnant in the large $\eta$ region, using a simple model based on SU(6) wave-function [22].

- The polarizations of $\Sigma^+$ and $\Sigma^-$ are sensitive to different pictures of spin transfer in fragmentation process, and thus can distinguish whether SU(6) or DIS picture is suitable for the spin transfer in fragmentation. The results for $\Sigma^+$ and $\Sigma^-$ differ in sign because of the sign difference between $\Delta u(x)$ and $\Delta d(x)$, and the magnitude of $\Sigma^-$ polarization is about one half of $\Sigma^+$ polarization due to the size difference between $\Delta u(x)$ and $\Delta d(x)$.

- The results for $\Lambda$, $\Xi^0$ and $\Xi^-$ hyperons are in general smaller compared with $\Sigma^\pm$ polarization as their contributions of $s$ quark are smaller than that of $u$, $d$ quarks to $\Sigma^\pm$. Their polarizations have similar shapes at $\eta < 3$ because they are all dominated by the $s$ quark’s contribution, and the different shapes at $\eta \approx 4$ come from the different effects of beam remnants.

- The polarizations of $\Lambda$, $\Xi^0$ and $\Xi^-$ are sensitive to different choices of polarized parton distribution functions rather than different spin transfer pictures in fragmentation. The sensitivity mainly comes from the strange sea quark’s contribution. Their polarizations can thus provide sensitivity to the helicity distribution function of strange quark $\Delta s(x)$ with hyperon $\eta$ up to 3.5. At even larger $\eta$, the sensitivity decreases as the contribution of $s$ quark drops to zero and the beam remnant’s contribution shows up.

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With the same procedure, we also evaluated the polarizations for anti-hyperons $\Sigma^-$, $\Sigma^+$, $\Lambda$, $\Xi^0$ and $\Xi^+$. The general shapes of their polarizations are quite similar as those obtained with higher $p_T > 8$ GeV in mid-rapidity [3], but the magnitudes are smaller. The polarizations for $\Lambda$, $\Xi^0$ and $\Xi^+$ at $2.5 < \eta < 4$ are similar both in size and in shape. Unlike their anti-particles, the contribution from beam remnant is negligible here. Their polarizations are all sensitive to different sets of polarized parton distribution functions as their polarizations are dominated by contribution of $\bar{s}$ quark. The polarizations of $\Lambda$, $\Xi^0$ and $\Xi^+$ thus provide sensitivity to $\Delta \bar{s}(x)$. The size of $\Sigma^-$ and $\Sigma^+$ polarization is smaller than that for the $\Lambda$ and $\Xi$ hyperons, and their polarizations are dominated by the contributions from $\bar{u}$ and $\bar{d}$ quarks. The $\Sigma^-$ and $\Sigma^+$ polarizations show sensitivity to $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$ with $\eta$ up to 4. The results for $\Sigma^-$ and $\Sigma^+$ polarizations differ

FIG. 3: Longitudinal polarization for $\Lambda$, $\Sigma^+$, $\Sigma^-$, $\Xi^0$ and $\Xi^-$ hyperons with $p_T \geq 3$ GeV in $pp$ collisions at $\sqrt{s} = 500$ GeV with one beam longitudinally polarized versus $\eta$. Positive $\eta$ is taken along the direction of the polarized beam.

FIG. 4: The same as Fig.3 for the polarizations of anti-hyperons $\Sigma^-$, $\Sigma^+$, $\bar{\Lambda}$, $\bar{\Xi}^0$ and $\bar{\Xi}^+$. 
in sign because of the sign difference in $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$ in the “valence” set of GRSV2000.

We also make calculations for (anti-)hyperons with $p_T > 2$ GeV at $\sqrt{s} = 200$ GeV. The main features of their polarizations remain the same as the above results at $\sqrt{s}=500$ GeV, and just the size of the polarizations is slightly smaller. This is because of the smaller fractional contributions from the quarks. In addition, in this case the contribution from beam remnant becomes larger at $\eta > 3$ as the $p_T$ is a bit lower, and this may introduce some uncertainty to the evaluations of their polarizations.

In the case that the separation of hyperon and anti-hyperon is difficult with forward detectors as proposed in the STAR detector upgrade [11], we also make corresponding calculations by combining hyperon and its anti-particle. The combined results of polarization are shown in Fig. 5 for $\Sigma^+ + \Sigma^-$ and $\Lambda + \bar{\Lambda}$ versus $p_T$ for $2.5 < \eta < 3.5$ in $pp$ collisions at $\sqrt{s} = 500$ GeV. It shows that a precision measurement of $\Sigma^+ + \Sigma^-$ polarization is able to distinguish different models for the spin transfer in fragmentation process, and the polarization of $\Lambda + \bar{\Lambda}$ may provide useful information for the helicity distribution functions of strange sea quarks.

In summary, we have investigated the longitudinal polarizations of hyperons and anti-hyperons in polarized $pp$ collisions in the forward region of $2.5 < \eta < 4$. The results show that $\Sigma^+$ polarization in this kinematic region is significant and can distinguish the two spin transfer pictures SU(6) and DIS in the fragmentation process. The polarizations of $\Lambda$ and $\bar{\Lambda}$ can provide sensitivity to strange sea and anti-sea quark polarization in polarized nucleon. Precision measurements at the RHIC $pp$ collider should be able to test these predictions and thus provide new insights into the polarized fragmentation process and the strange sea quark polarization in the nucleon.

We thank Prof. Zuo-tang Liang for the helpful discussions. This work was supported in part by the National Natural Science Foundation of China under the approval Nos. 10525523 & 10975092, and by SRF for ROCS, SEM.

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