High-Energy Polarimetry at RHIC

Boris Z. Kopeliovich
Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany
Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia

This paper is dedicated to the memory of my teacher
Professor Lev Lapidus

Abstract

We compare a few types of high energy reactions which seem to be practical for polarimetry at RHIC. Coulomb-nuclear interference (CNI) in $pp$ elastic scattering leads to a nearly energy-independent left-right asymmetry $A_N(t)$ at small $t$. The systematical uncertainty of this method is evaluated to be $\sim 10\%$.

The CNI in proton-nucleus elastic scattering is predicted to result in larger values of $A_N(t)$ and occurs at larger momentum transfer than in $pp$ elastic scattering. This energy independent asymmetry can be used for the polarimetry.

As an absolute polarimeter one can use elastic $pp$ scattering on a fixed target at large $|t| \sim 1 - 1.5\ GeV^2$, where $A_N(t)$ is reasonably large and nearly energy independent. Although it cannot be reliably calculated, one can calibrate the polarimeter by measuring the polarisation of the recoil protons.

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1. Introduction

High-energy polarised proton beams are under construction at RHIC and a wide program of polarisation phenomena study is planned. However, one faces the problem of measurement of the polarisation of the beams. A prospective polarimeter is supposed to be able to provide a fast (minutes/hours) measurement of the polarisation in a wide energy range ($25\,\text{–}\,250\,\text{GeV}$) with a statistical error within 5\% and a systematical uncertainty of the same order [1].

The single asymmetry is believed to vanish at high energies, what is, however, not true in some cases which can be used for high-energy polarimetry.

The main problem is lack of reliable and accurate data on analysing power $A_N$ of hadronic reactions at high energy. One can either use available data on analysing power, or to measure it in the same experiment. In some cases $A_N$ can be reasonably well predicted theoretically.

This note is not a review of the present status of high energy polarimetry, but includes only a few examples of polarimeters which seem to be practical for RHIC.

2. Pion polarimeter

Polarisation in inclusive reactions at fixed Feynman $x_F$ is expected to be nearly energy independent (Feynman scaling) in the high-energy limit. In some cases it reaches a few tens percent at large $p_T$ and $x_F$. As an example, reaction of inclusive pion production,

$$p + p \rightarrow \pi^\pm + X$$

exhibits these features [2]. Therefore, this reaction is a very good candidate [1] for polarimetry at RHIC, provided that its analysing power is known. Unfortunately, the measurement of analysing power $A_N(p_T, x_F)$ of (1) was performed at high energies only once [2], at energy $E = 200\,\text{GeV}$ and with a proton target. The polarimeter, however, is supposed to work in the full beam energy range from AGS to the maximal energy of RHIC $E_{\text{max}} \approx 250\,\text{GeV}$ in
the lab frame. Therefore, energy independence of $A_N$ is assumed in \cite{1}. Moreover, only a carbon target is feasible to be used at RHIC. Lacking data for reaction (1) on a carbon one is enforced either to assume no $A$-independence of the analysing power \cite{1}, or to measure it with low energy beam of known polarisation and assume that the analysing power does not change through the whole energy range of RHIC.

We are going to look more attentively at these assumptions and their justification.

2.1 A-dependence

$A$-dependence of inclusive particle production at large transverse momentum is known to exhibit the so called Cronin effect \cite{3}, namely, the exponent $\alpha$ describing effectively the $A$-dependence ($A^\alpha$) exceeds one, \textit{i.e.} the inclusive production rate on a nucleus is more than $A$ times larger than that on a free nucleon. It looks like the bound nucleons help each other producing the high-$p_T$ particle. Although no satisfactory numerical explanation of this effect is still known, the source the enhancement is well understood on a qualitative level. The projectile partons experience multiple interactions in the nucleus, and the higher the \( p_T \) is, the larger is the mean number of rescatterings. This is because the large \( p_T \) is distributed over many interactions with smaller momentum transfer. The multiple interactions lead to a steeper $A$-dependence, since each interactions adds a factor $\sim A^{1/3}$ due to integration over the longitudinal position of the interaction point. Thus, the enhanced $A$-dependence is a clear signal of multiple rescattering. A model-independent relation between the exponent $\alpha$ and the mean number of rescatterings is derived in \cite{4}.

\[
\langle n \rangle = 3\alpha - 1 + \sigma_0\langle T \rangle
\]

Here $\sigma_0 = (\int dk^2 \frac{d\sigma}{dk^2_T})$ is the total parton - nucleon cross section. $\langle T \rangle$ is the mean nuclear thickness,

\[
\langle T \rangle = \frac{1}{A} \int d^2b \ T^2(b)
\]

\footnote{Compared to \cite{1} Eq. (2) includes one additional interaction which triggers the process (1).}
where

\[ T(b) = \int_{-\infty}^{\infty} dz \rho_A(b, z) \]  

is the nuclear thickness function at impact parameter \( b \). The nuclear density \( \rho_A(b, z) \) depends on \( b \) and longitudinal coordinate \( z \).

Data [5] on pion inclusive production show that at \( p_T = 1 \) GeV the exponent \( \alpha \approx 0.9 \). The mean nuclear thickness of carbon with realistic nuclear density [6] is \( \langle T \rangle_C = 0.33 \) fm\(^{-2} \).

According to (2) the mean number of parton rescatterings in carbon is \( \langle n \rangle_C = 2 \).

One comes to a similar result in a different way comparing the probabilities of single and double rescatterings.

\[ \frac{W_2(p_T)}{W_1(p_T)} = \frac{1}{2} \sigma_0 \langle T \rangle \exp(p_T^2 B_{qN}/2) \]  

(5)

For a rough estimate we can use the quark - nucleon interaction cross section given by the constituent quark model \( \sigma_0 \sim 10 \) mb. We assume in (4) a Gaussian \( p_T \)-dependence of the quark-nucleon inclusive cross section. The slope parameter of quark-quark scattering is related to the mean radius of the constituent quark [7] \( R_q^2 \approx 0.44 \) fm\(^2 \). Correspondingly, \( B_{qN} \approx R_q^2/3 \approx 3.5 \) GeV\(^{-2} \). Using (3) we can estimate the ratio of double to single scattering contributions at \( (W_2/W_1)_C \approx 1 \) at \( p_T^2 = 1 \) GeV\(^2 \), what agrees reasonably well with the previous evaluation [2].

Neglecting the higher that double rescattering terms we can estimate the analysing power of reaction (1) on a nuclear target. Since the projectile quark interacts incoherently with the nucleus at large \( p_T \), one can write,

\[ A_N^{(A)}(p_T) = \left[ 1 + \frac{W_2(p_T)}{W_1(p_T)} \right]^{-1} \left\{ A_N^{(N)}(p_T) + \frac{2}{\pi} \sigma_{qN} B_{qN} \exp(B_{qN} p_T^2) \langle T \rangle \right. \\
\times \left. \int d^2 k_T A_N^{(N)}(k_T) \exp(-B_{qN} k_T^2) \exp \left[-B_{qN} (p_T - k_T)^2 \right] \right\} \]  

(6)

This formula can be used to predict \( A \)-dependence of polarisation effects in inclusive reactions on moderately heavy nuclei and at moderately high \( p_T \) (otherwise higher order multiple scattering terms are important). This is not, however, our present objective. We need just a rough estimate to check whether one can expect a weak or a strong \( A \)-dependence.
The single asymmetry $A_N^{(N)}(p_T)$ in inclusive pion production off a free proton as measured in the E704 experiment \cite{2} is nearly zero at $p_T < 0.5 \text{ GeV}$, linearly grows with $p_T$ up to $p_T \approx 1 \text{ GeV}$, and is approximately constant at higher $p_T$. For an estimate we fix $A_N^{(N)}(k_T)$ in the second term in (6) at the mean value of momentum transfer in each of the double scatterings $k_T^2 = p_T^2/2$. Then the asymmetry in pion production off carbon at $p_T = 1 \text{ GeV}$ is expected to be $A_C^{(C)}(p_T = 1 \text{ GeV}) \approx \frac{1}{2} A_N^{(N)}$. Thus, we expect quite a strong $A$-dependence of the analysing power of reaction (4).

2.2 Energy dependence

At high Feynman $x_F$ the cross section of an inclusive reaction can be described by a triple-Regge graph. An example for $pN \rightarrow \pi^+X$ is shown in Fig. 1.

![Figure 1: The triple-Pomeron graph for the cross section of the reaction $pN \rightarrow \pi^+X$. The thin dashed line shows that only the absorptive part of the amplitude is included. The upper legs are the nucleon Reggeons, the bottom one is either the Pomeron or the leading Reggeons, $\omega, f, \rho, a_2$.](image)

The bottom leg of this graph can be either the Pomeron, or a Reggeon ($f, \omega, \rho, a_2$). In the latter case the inclusive cross section at fixed $x_F$ decreases $\propto 1/\sqrt{s}$. However, this
bottom part of the graph can be treated as an absorptive part of the amplitude of elastic scattering of the $N$-Reggeon (upper legs in Fig. 1) on the target. This amplitude is subject to exchange degeneracy, therefore, the Reggeons should cancel each other in the imaginary part. Nevertheless, exchange degeneracy is known to be broken in $pp$ total cross section. This is why $\sigma_{tot}^{pp}(E)$ decreases at low and moderate energies. To evaluate the energy dependence we can use the the data on $\sigma_{tot}^{pp}(E)$. The energy $E$ should be taken at smaller value than the energy $E_{pp}$ of reaction (1):

$$E = (1 - x_F)E_{pp}$$  \hspace{1cm} (7)

For example, a variation of the beam energy $E_{pp}$ in reaction (1) from 25 GeV to 250 GeV at $x_F = 0.8$ corresponds to the energy $E$ variation for $\sigma_{tot}^{pp}(E)$ from 5 GeV to 50 GeV. The cross section $\sigma_{tot}^{pp}(E)$ decreases in this interval by nearly 10%. This estimate shows that the energy dependence can be substantial.

Another source of energy dependence is a strong variation of the $A$-dependence of the inclusive cross section at high $p_T$ with energy [5]. It leads to variation of the cross section on carbon by 30% in the energy interval 200−400 GeV. We would expect even more substantial change in the RHIC energy range. This means, particularly, that even if the $A$-dependence is known at one energy, one cannot assume it to be the same in the whole energy range.

2.3 Isospin dependence

Another source of nuclear dependence of the asymmetry is a possible difference between proton and neutron targets. The triple-Reggeon graph in Fig. 1 is sensitive to the isospin of the target if the bottom leg of this graph is an isospin vector Reggeon ($\rho$, $a_2$). As was mentioned above, the exchange degeneracy leads to a substantial cancellation between $\rho$ and $a_2$. These Reggeons contribute to the absorptive part of the $N$-Reggeon - nucleon amplitude much less than the dominant $\omega$ and $f$ Reggeons. Therefore, we do not expect a strong isospin dependence of the asymmetry. To evaluate the effect we can use the known
difference between $\sigma_{tot}^{pp}(E)$ and $\sigma_{tot}^{pn}(E)$. The energy $E$ should be taken at a smaller value (7).

3. Coulomb - nuclear interference (CNI)

This method of polarimetry has been under discussion since 1974 when a nearly energy independent asymmetry due to interference between electromagnetic and hadronic amplitude was claimed in [8, 9]. Assuming the hadronic amplitude to be spin-independent at high energies one can predict the single spin asymmetry $A_N(t)$ in elastic $pp$ scattering, which behaves at small $t$ as [8],

$$A_N^{pp}(t) = A_N^{pp}(t_p)\frac{4y^{3/2}}{3g^2 + 1},$$

where $y = |t|/t_p$ and $t_p = 8\sqrt{3}\pi\alpha/\sigma_{tot}^{pp}$ is the value of $|t|$ where the asymmetry has a maximum value,

$$A_N^{pp}(t_p) = \frac{\sqrt{3t_p}(\mu_p - 1)}{4m_p},$$

with the proton magnetic moment $\mu_p$. We neglect in (9) the real part of the hadronic amplitude and the Bethe phase. Both can be easily incorporated in this formula [9].

The first measurements of $A_N^{pp}(t)$ by the E704 collaboration [13] at 200 GeV confirmed prediction [8]. The data are compared with (9) in Fig. 2.

The CNI asymmetry is nearly energy independent (it depends only on $\sigma_{tot}^{pp}$ and the ratio of real to imaginary parts of the forward elastic amplitude, which are pretty well known in the energy range under discussion) and can serve for polarimetry at high energies.

It was noticed, however, in [10, 12] that presence of a spin-flip component of the hadronic amplitude affects the value of CNI asymmetry. The relative deviation of $A_N$ from the nominal value (1) is $-2\text{IM}r_5/(\mu - 1)$ [8, 9], where $r_5 = (2m/\sqrt{-t})\phi_5/\text{Im}(\phi_1 + \phi_3)$ [10]. This might be a substantial correction to the predicted asymmetry (9).

\[^{\dagger}\text{According to our definition } r_5 \text{ is twice as small as the anomalous magnetic moment of the Pomeron } \mu_P \text{ introduced in [10]. Our definition of } r_5 \text{ is also different by } 90^0 \text{ phase from } \tau \text{ used in [12].}\]
Figure 2: Data [13, 23] for the asymmetry in polarised elastic $pp$ scattering in the CNI region at 200 GeV. The curve predicted in [8] corresponds to (8).

Such a sensitivity to the unknown spin-flip component of the Pomeron gives an unique opportunity to measure it [10] provided that the beam polarisation is known. However, it brings an uncertainty to the CNI polarimetry [12].

3.1 What do we know about the hadronic spin-flip at high energy and small $t$?

Even in this circumstances the situation with CNI polarimetry is not hopeless. One can find solid arguments, both experimental and theoretical, reducing the uncertainty down to a few percent [14].

- The results of the E704 experiment [13] depicted in Fig. 2 show no deviation within the (quite large) error bars from the prediction [8, 9] based on a spinless hadronic amplitude. Therefore the data impose an upper limit on a possible hadronic spin-flip.
We cannot expect a substantial real part of this amplitude at high energy, otherwise it would interfere with the imaginary non-flip part resulting in a large polarisation in pp elastic scattering, contradicting the data (see in [14]). If spin-flip amplitude $\phi_5$ is imaginary, the analysis [22, 12] of data [13] leads to a restriction $\text{Im} \ r_5 < 0.15$.

- The data on asymmetry in $\pi^+p$ and $\pi^-p$ elastic scattering, if they are summed, may have contribution only from the Reggeons with even signature, i.e. from the interference between the Pomeron and the $f$-Reggeon. The upper limit on the Pomeron spin-flip component corresponds to a pure non-flip $f$-Reggeon (provided that spin-flip to non-flip ratios for $f$ and $P$ have the same sign, what looks very natural, for instance in the model of the $f$-dominated Pomeron). The analysis of available data in the energy range $6 - 14 \text{ GeV}$ performed in [16, 14] leads (assuming Regge factorisation) to a restriction $r_5 < 0.1$, which is in agreement with the above estimate.

Although this analyses is performed at quite low energies (available data at high energies are not sufficiently precise), we do not expect a substantial energy dependence of $r_5$. According to the recent results from HERA for the proton structure function $F_2(x, Q^2)$, the steepness of energy (or $1/x$) dependence of $F_2$ is controlled by the mean size ($1/Q^2$) of the hadronic fluctuations of the virtual photon: the smaller the size is, the steeper is the growth of $F_2$. It is found in [13, 10] (see below) that the spin-flip part of the amplitude originates from a smaller size configurations of the proton than the non-flip part. Therefore, one can expect a rising energy dependence of $r_5$. However, even a most extreme evaluation of this effect, assuming a scale of $10 \text{ GeV}^2$, results in a growth of $\text{Im} \ r_5$ from $E = 10 \text{ GeV}$ to $250 \text{ GeV}$ by only 30%.

- A model independent (although with some approximations) amplitude analyses [17] of pion-proton elastic and charge-exchange scattering data shows that the energy-independent part of the iso-singlet (in t-channel) spin-flip amplitude corresponds to $\text{Im} \ r_5$, which does not exceed 15%. This analysis, however, overlaps with the one we
discussed previously, since it is essentially based on the same data.

- A perturbative QCD evaluation of the Pomeron spin-flip amplitude was done in \[13, 10\]. It is widely believed that the perturbative Pomeron contains no spin-flip component because the quark-gluon vertex conserves helicity. However, the proton helicity differs from the sum of the helicities of the quarks, because those have transverse motion, \textit{i.e.} their momenta are not parallel to the proton one. This fact can lead to a nonzero proton spin-flip. Calculations performed in the nonrelativistic constituent quark model (in the Breit frame) \[10\] show, however, that these corrections cancel if the proton has a symmetric quark structure. Only in the case when a component with a compact \(qq\) pair (diquark) is enhanced in the proton wave function, the Pomeron-proton vertex acquires a nonzero spin-flip part. The smaller the mean diquark radius \(r_D\) is, the larger is \(r_5\). For reasonable values of \(r_D > 0.2\) \(fm\) the spin flip fraction \(\text{Im} r_5\) ranges within 10\% in the CNI region of momentum transfer.

Although oversimplified, these calculations demonstrate that within perturbative QCD there is no source of a large spin-flip component of the Pomeron. However, the non-perturbative effects might be a potential source of a spin-flip amplitude.

- One can effectively include the non-perturbative effects switching to hadronic representation, which should be equivalent to the QCD treatment due to quark-hadron duality. The Reggeon-proton vertex is decomposed over hadronic states in \[18\] (see also \[19\]) using a two-pion approximation for the \(t\)-channel exchange and a two-component \((N, \Delta)\) intermediate state for the nucleon. It turns out that the resulting proton - Reggeon spin-flip vertex essentially correlates with the isospin in \(t\)-channel \[19\]. Namely, the contributions of intermediate \(N\) and \(\Delta\) nearly cancel each other for the isosinglet Reggeons \((P, f, \omega)\) resulting in \(\text{Im} r_5 \approx 0.05\). On the other hand, \(N\) and \(\Delta\) add up in the isovector amplitude \((\rho, a_2)\) leading to an order of magnitude larger value of \(r_5\).

This approach includes effectively the non-perturbative QCD effects and is based on
completely different approximations than the perturbative calculations [15, 10]. Nevertheless, it leads to a similar evaluation for the Pomeron $r_5$. It makes these theoretical expectations quite convincing.

Summarizing our experimental and theoretical knowledge of the hadronic spin-flip at high energy and small $t$ we conclude that the systematical uncertainty of CNI polarimetry does not exceed 10%.

Note that CNI method can be used both in the collider and fixed target experiments. Provided that a polarised proton jet target will be available one can calibrate the CNI polarimeter, i.e. eliminate the uncertainty related to the hadronic spin-flip component. This is another potential advantage of the CNI polarimeter compared to one based on inclusive pion production. Indeed, it can be calibrated on a polarised target only if the pion is detected in reversed kinematics, i.e. in the fragmentation region of the polarised target, what is difficult to do.

3.2 CNI on nuclear targets

The spin structure of the elastic proton-nucleus scattering is simpler than that in $pp$. There are only two spin amplitudes if the nucleus is spinless, otherwise other amplitudes are suppressed by factor $1/A$. Besides, the main contribution to the $pp$ spin-flip amplitude $\phi_5$, which comes mainly from the iso-vector Reggeons $\rho$ and $a_2$, are either forbidden or suppressed by $1/A$. Thus, the uncertainty of CNI polarimetry may be substantially reduced.

The $t$-dependence of single asymmetry in polarised elastic $p - A$ scattering in the CNI region is similar to that in $pp$ scattering. The position $t_p$ of the maximum of the asymmetry and the value of $A_N(t_p)$ are controlled by the magnitude of the $\sigma^{pA}_{tot}$ and the electric charge of the nucleus $Z$ (compare with (8)-(9)),

$$t_p^{pA} = \frac{Z\sigma^{pp}_{tot}t_{pp}}{\sigma^{pA}_{tot}t_p}.$$  

\[11\]
Correspondingly,
\[
A^{pA}_{N}(t_{pp}^{pA}) = \sqrt{\frac{Z \sigma^{pp}_{tot}}{\sigma^{pA}_{tot}}} A^{pp}_{N}(t_{pp}^{pp}) . \tag{11}
\]

It turns out that the position of the maximum of \(A^{pA}_{N}\) and its value are not much different from that in \(pp\) scattering.

It is proved in \[20\] that if \(r_{5}\) is imaginary, it is independent of \(A\), i.e. is the same as the iso-singlet part or \(r_{5}\) in \(pp\) elastic scattering. Therefore, the hadronic spin-flip brings the same uncertainty to CNI polarimetry on nuclear targets.

The differential cross section of proton - nucleus elastic scattering exhibits a diffractive structure, i.e. series of maxima and minima \[21\]. This is known to be a result of destructive interference between different terms in the multiple scattering series. Imaginary part of the elastic amplitude changes sign at positions of the minima. The first minimum happens at \(|t| \sim 3/R_{A}^{2}\), which is in the CNI region and for heavy nuclei is quite close to \(|t_{p}|\) given by \((11)\).

As soon as the imaginary part of the hadronic component of the non-flip elastic amplitude changes sign, the CNI asymmetry does the same. We expect a nontrivial behaviour of \(A_{N}(t)\) in the vicinity of the minimum of the differential cross section, what resembles the \(pp\) elastic scattering at much larger \(t\) (see the next section). Namely, \(A_{N}(t)\) reaches a sharp positive maximum, then changes sign and develops a sharp negative minimum.

Indeed, the CNI asymmetry is given by expression,
\[
A^{pA}_{N}(s, t) \left( \frac{d \sigma^{pA}_{el}}{dt} \right) = \frac{Z \alpha \sigma^{pA}_{tot}}{2m_{p}q} F^{C}_{A}(q^{2}) F^{H}_{A}(q^{2}) \left[ \mu_{p} - 1 - 2 \text{Im} \ r_{5} \right] , \tag{12}
\]
where \(t = -q^{2}\), and \(q\) is the transverse momentum transfer,
\[
\sigma^{pA}_{tot} = 2 \int d^{2}b \left[ 1 - e^{-\frac{1}{2} \sigma^{pA}_{tot} T(b)} \right] . \tag{13}
\]
Here \(T(b)\) is the nuclear thickness function defined in \((1)\).

The electromagnetic and hadronic nuclear formfactors in \((12)\) read,
\[
F^{C}_{A}(q^{2}) = \frac{1}{A} \int d^{2}b \ e^{i \vec{q} \vec{b}} T(b) , \tag{14}
\]
\[ F_A^H(q^2) = \frac{1}{2\sigma_{\text{tot}}^p} \int d^2b \ e^{i\vec{q}\cdot\vec{b}} \left[ 1 - e^{-\frac{1}{2}\sigma_{\text{tot}}^{pN}T(b)} \right]. \]  \quad (15)

The elastic \( pA \) differential cross section reads,

\[
\frac{d\sigma_{ei}^{pA}}{dt} = \frac{\left[ \sigma_{\text{tot}}^{pA} F_A^H(t) \right]^2}{16\pi} + 4\pi \left( \frac{Z\alpha F_C^N(t)}{t} \right)^2 \quad (16)
\]

We neglect the ratio of real to imaginary parts of the \( pA \) elastic amplitude, which is smaller than that in \( pp \) scattering. The Bethe phase is neglected as well, although it might be a substantial correction for heavy nuclei [22]. These corrections are to be done [20] for a precise prediction, but we can neglect them to demonstrate the magnitude of the polarisation effects.

Our predictions for the CNI contribution to the single asymmetry for elastic scattering of polarised protons on carbon and lead are shown in Fig. 3. As we expected, the dip structures in the differential cross section reflect in a nontrivial \( t \)-dependence of \( A_N(t) \).

![Figure 3: Asymmetry in polarised proton scattering on carbon and lead, calculated using (12). The experimental point for \( pC \) scattering is from [23].](image_url)

In the colliding mode heavy nuclei have \( 1/Z \) smaller scattering angle than protons at the
same momentum transfer. Therefore, they cannot be detected in the traditional CNI region of \( t \sim 10^{-3} \text{ GeV}^2 \). As soon as a much stronger CNI asymmetry is expected in the vicinity of the first diffractive minimum in the differential cross section, it might be feasible to do measurements in this range of momentum transfer with the \( p - A \) collider at RHIC. The maximum of the asymmetry for carbon, \( A^C_N(t) \approx 0.25 \) is expected at \( |t| = 0.078 \text{ GeV}^2 \), what corresponds to the same scattering angle as in \( pp \) elastic scattering at \( |t| \approx 2 \times 10^{-3} \text{ GeV}^2 \). These measurements can be performed with a fixed carbon target as well.

The differential cross section of \( p - ^4\text{He} \) elastic scattering exhibits a well developed minimum at \( |t| \approx 0.2 \text{ GeV}^2 \) We expect a large asymmetry in the vicinity of the dip \([20]\), which can be reliably calculated. The scattering angle of the \(^4\text{He} \) is the same as in \( pp \) scattering at \( |t| \approx 0.05 \text{ GeV}^2 \), which is easy to measure in the whole RHIC energy range. An additional advantage of \(^4\text{He} \) is a lack of excitations.

4. Polarimetry with elastic \( pp \) scattering at large \( |t| \)

I addition to the CNI region of very small \( t \) the single asymmetry in \( pp \) elastic scattering is known to be quite large and nearly energy independent at large \( |t| \sim 1 - 2 \text{ GeV}^2 \) \([25, 26, 27]\) (see Fig. 4). This is related to the dip structure of the differential elastic \( pp \) cross section in a similar way as we have seen above for nuclear targets. The imaginary part of the non-flip part of the amplitude is unavoidably small near the point \( t_0 \) where it changes sign, particularly, as small as the spin-flip part. Due to this fact \( A_N(t) \) is large and changes sign at \( t = t_0 \). It is true at any energy, despite the decreasing energy dependence of the spin-flip amplitude.

To make use of this effect for polarimetry one needs to know the analysing power \( A_N(s, t) \). The available data shown in Fig. 4 allow only a crude evaluation of the beam polarisation. For a precise polarimetry the analysing power is to be measured with a high accuracy, what can be done in the same experiment. One should take the advantage of equality between the asymmetry of elastic scattering with a polarised beam and the polarisation of final protons.
Figure 4: Single asymmetry in polarised pp elastic scattering at $p_{lab} = 150, 200$ and 300 GeV/c [25, 26, 27].

with an unpolarised beam. Then, one can measure the polarisation of recoil protons instead of $A_N(s, t)$. The kinetic energy of the recoil proton in the rest frame of the target is quite low,

$$E_{kin} = \frac{|t|}{2m_p}. \quad (17)$$

In this energy range $E_{kin} \approx 600$ MeV spin effects are known to be quite strong. One can use a standard carbon polarimeter, which can be calibrated to a high precision at any of available polarised beam facilities in this energy range (e.g. at IUCF).

Thus, this method of polarimetry includes two stages (provided that a calibrated low-energy carbon polarimeter is available). First, one has to calibrate the polarimeter with an unpolarised proton beam, i.e. to measure the recoil proton polarisation $P(s, t) = A_N(s, t)$ at $|t| \sim 1 − 1.5$ GeV$^2$ at different energies. Then one can remove the recoil proton polarimeter and measure the left-right asymmetry with a polarised beam. This asymmetry divided by $A_N$ gives the beam polarisation.

One can also use a fixed nuclear target, since no depolarisation of the recoil proton in nuclear matter is expected. However, the inelastic background is larger because of the broadening of the recoil proton angle by Fermi motion.

Note that the results of such measurement would allow to calibrate the CNI polarimeter,
to eliminate the uncertainty of unknown hadronic spin-flip. One can use both small and large $|t|$ polarimeters within the same experiment on elastic $pp$ scattering. This would provide a double check of the results.

It worth also noting that with a polarised target one does not need the second scattering and the low-energy carbon polarimeter.

5. Summary

Comparison of three possible types of polarimeters for the RHIC polarised beams led us to a conclusion that probably the best is one which uses elastic $pp$ and $pA$ scattering. Small $|t|$ scattering on an unpolarised target is based on theoretically predicted CNI analysing power, which has a relative uncertainty within 10%. With nuclear targets one can perform the measurements at larger $|t|$ where the differential cross section has a minimum. In this region the CNI leads to dramatic polarisation effects.

Elastic $pp$ scattering at large $|t| \sim 1 - 1.5 \, GeV^2$ on a fixed target can be calibrated using a second scattering of the recoil low-energy proton. This method, if realistic\(^5\), is potentially able to provide a most accurate, uncertainty free measurement of the beam polarisation. It seems that most effective is usage of both methods, which can be combined within the same experiment on elastic $pp$ scattering.

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\(^5\)preliminary evaluation shows that such a polarimeter is feasible
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