Physics Program with Tagged Forward Protons at STAR/RHIC

J.H. Lee for the STAR Collaboration *
Brookhaven National Laboratory - Physics Department
Upton, NY 11973 - U.S.A.

A new effort to explore the diffractive regime in polarized \( p + p \) collisions in a broad high energy range (\( \sqrt{s} = 200 - 500 \) GeV) has been initiated with the STAR detector at RHIC. Staged implementation of multiple Roman Pot stations for tagging the forward proton in the diffractive processes will enable searches for the centrally produced for the possible gluon bound state via double Pomeron exchange process and the theoretically expected Odderon state in QCD by studying spin-dependent elastic scattering in a wide \( t \)-range with polarized \( p + p \).

1 Introduction

Diffractive processes at high energies are believed to be occurring via the exchange of a color singlet object (the “Pomeron”) with the same quantum numbers as the vacuum (\( J^{PC} = 0^{++} \)) \(^2\). The Pomeron is considered as a dynamical system rather than a particle which is expected to dominate exchange mechanisms at asymptotic energies. Since there is no color exchanged between the Pomeron and the parent nucleon, a rapidity gap in the final state emerges as a characteristic signature of diffractive events. Depending on the distribution of the gap and number of outgoing particles with same quantum number of initial particles, diffractive processes can be classified as elastic scattering, single diffraction (SD), or double diffraction (DD). Even though properties of diffractive scattering are described by the phenomenology of Pomeron exchange in the context of Regge theory, the exact nature of the Pomeron still remains elusive. Main theoretical difficulties in applying QCD in diffraction are due to the intrinsically non-perturbative nature of the process in the kinematic and energy ranges of the data currently available. The experimental challenge is identifying and reconstructing forward protons kinematically very close to the beam.

The diffractive physics program at the Relativistic Heavy-Ion Collider (RHIC) is a new experimental program to study elastic and inelastic diffractive processes (SD, DD) with tagged forward protons in polarized \( p + p \) collisions at \( \sqrt{s} = 200 - 500 \) GeV. For the elastic program, the collider energy range is previously unexplored, and the measurements will serve as an important bridge between vast lower energy data and limited measurements at higher energy data. The energy range, particularly with polarized \( p + p \) collisions, is suitable as a testing ground for the long standing theoretical evidence in QCD for the existence of the Odderon which is the \( C = P = -1 \) counterpart to the Pomeron \(^2\). The main physics motivation for the inelastic diffraction program is for searching for a gluonic bound state whose existence is allowed in pure gauge QCD, but for which no unambiguous candidate has been established.

---

*This work was supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
2 Tagging Forward Protons in Diffractive Processes

Although identification of a rapidity gap can be utilized for studying diffractive processes, it is imperative to tag and reconstruct the forward proton to eliminate the ambiguity of a rapidity gap tag, which can be contaminated by background due to low multiplicity non-diffractive processes. The rapidity gap tag also does not provide information on whether the initial proton remains intact after the collision or is excited into a low-mass state with small energy loss, which could still yield a rapidity gap. Tagging forward protons, i.e., detecting scattered protons in diffractive processes requires reaching inside of the beam pipe since the scattering angles are very small of the order of µrad to a few mrad. This can be achieved by exploiting the technique of the “Roman Pot” (RP) which has been developed and used at the ISR [3]. At RHIC, the technique has been successfully used for studying elastic scattering in the experiment pp2pp [4]. By detecting the scattered proton in RPs, one can reconstruct its momentum from the measured positional and directional information of the protons in the given beam optics and thus derive two key variables characterizing kinematics of the collisions: four momentum transfer \( t = (P_1 - P)^2 \) and longitudinal momentum fraction \( \xi = (1 - x_F) \), where \( x_F = 2p_L/\sqrt{s} \). \( \xi \) is simply related to the momentum fraction of the proton carried by the Pomeron (\( IP \)), commonly refereed as \( x_F \).

For a wide kinematic coverage, a staged implementation of RP is considered. For the initial phase of the new program (Phase I), which probes for probing small-\( t \) reaction, the Roman Pots used for the pp2pp experiment have been integrated with STAR detector [5]. They are positioned at ±55.5, ±58.5m from the nominal interaction point (IP). Each RP contains four planes of silicon strip detectors (SSD) (two vertical and two horizontal) to provide redundancy for the track reconstruction. Figure 1 shows the distribution of accepted positions of the elastically scattered protons in SSD in two RP stations at \( \sqrt{s} = 200 \text{ GeV} \) with the beam \( \beta^* = 21 \text{m} \) for minimum angular divergence. The corresponding accepted \( t \) range is \( 0.002 < \mid t \mid < 0.03 \text{ GeV}^2 \). During RHIC

\[ \frac{1}{2} |t| \text{ [GeV]} \]

![Figure 1: Y vs. X distribution of protons in the RPs for elastic events for the Phase I setup, which was used for RHIC/Run-9.](image1.png)

Figure 1: Y vs. X distribution of protons in the RPs for elastic events for the Phase I setup, which was used for RHIC/Run-9.

\[ \text{Acceptance} \]

![Figure 2: Acceptance of elastic events as a function of \( t \) for Phase I (hatched) and Phase II at \( \sqrt{s} = 500 \text{ GeV} \).](image2.png)

Figure 2: Acceptance of elastic events as a function of \( t \) for Phase I (hatched) and Phase II at \( \sqrt{s} = 500 \text{ GeV} \).
Run-9, ~70M of events, including ~30M of elastic events, were successfully taken with the Phase I set-up, and the data are currently being analyzed.

For Phase II, new sets of Roman Pot system will be designed and fabricated to be installed between RHIC DX-D0 magnets, 15-17m from the IP, extending the acceptance and the reach in \( t \) and \( \xi \) for a more optimized setting for inelastic diffractive program. Figure 2 shows the acceptance for elastic events for the Phase I and Phase II Roman Pot setups, and Fig. 3 shows the accepted \( t \)-distributions for inelastic diffractive events with the Phase I and Phase II Roman Pot setups.

For the inelastic diffractive studies, the Roman Pot systems will be used in conjunction with the STAR TPC to reconstruct and fully constrain events with a resonance in central production process. Since no special accelerator optics is required in this configuration for the Phase II set-up, running in parallel with other physics program in STAR is possible, and we will be able to utilize high luminosity for searches for rare physics processes.

### 3 Elastic Scattering: Searching for the Odderon

In elastic collisions with very small \( t \), there is interference between hadronic spin-flip helicity amplitudes, \( \phi_2 = (++|T|--) \) and \( \phi_4 = (-+|T|--) \), and the electromagnetic non-flip amplitude. This provides a sensitive tool to study the spin dependence of diffractive scattering at asymptotic energies and to search of the Odderon exchange [6]. The Odderon is a \( CP \) odd counterpart of the Pomeron which has been postulated from theoretical considerations, but has not yet been established experimentally. Because Pomeron and Odderon have opposite \( C \)-parities, it is expected in leading order, that if Pomeron and Odderon have the same asymptotic behavior, they are out of phase by approximately 90° [7,8]. Therefore, if they couple to spin, their interference with the electromagnetic non-flip amplitude will result in different \( t \)-dependences of the double spin asymmetries, \( A_{NN} \). The data taken with Phase I setup during the RHIC run-9 are expected to produce precise measurements of \( A_{NN} \) distributions covering the region where the strong \( t \)-dependence of the asymmetry is predicted. It is also predicted that there will be a difference in total cross-section and \( d\sigma/dt \) in \( p+p \) and \( \bar{p}+p \) collision in \( 0 < |t| < 1.5 \text{ GeV}^2 \) if the Odderon exists. The measurements [9] by UA4 in \( \bar{p} + p \) at \(\sqrt{s} = 546 \text{ GeV} \) can be compared with the RHIC data in \( p + p \) at \(\sqrt{s} = 500 \text{ GeV} \). Even though there will be \( \approx 10\% \) of difference (\( \Delta \sigma_{tot} \)) between the two energies, the overlap between the two data sets will make the measurements an unique and
Figure 4: Estimated phase-space distributions in effective mass for $M_X$ decaying to $\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$ (hatched), and $K^+K^-$ (cross-hatched) from 1M DPE events in $p + p \rightarrow p + M_X + p$ at $\sqrt{s} = 500$ GeV. The dotted line shows the effect mass distributions generated from the DPE events accepted in the Roman Pots (Phase II).

exciting opportunity for this challenging study [10]. Since the predicted $\Delta\sigma_{tot}$ is small ($\approx 3$ mb) and the most notable difference in $d\sigma/dt$ will be at $-t \approx 1$ GeV$^2$, the measurements require accurate measurement in a wide $t$ range requiring both Phase I and Phase II setups.

4 Inelastic Diffractive Double Pomeron Exchange Process: Searching for the Glueball

In the context of QCD, the Pomeron exchange is believed to be the exchange of a system of gluons. The double Pomeron exchange (DPE) process has been regarded as one of the potential channels of glueball production [11]. Two of the gluons in the DPE process could merge into a mesonic bound state without a constituent quark, a glueball in the central production $p + p \rightarrow p + M_X + p$. The central rapidity is expected to be spanning $\ln M_X$ and the rapidity gap in DPE process is $y_{beam} - y_{central} \approx 3$ units, which allows the maximum kinematical value of $M_X \approx 25$ GeV/$c^2$ with clean rapidity gaps.

Lattice QCD calculations have predicted the lowest-lying scalar glueball state in the mass range of 1500-1700 MeV/$c^2$, and tensor and pseudoscalar glueballs in 2000-2500 MeV/$c^2$ [11]. Experimentally measured glueball candidates for the scalar glueball states are the $f_0(1500)$ and the $f_J(1710)$ [12] in central production as well as other gluon-rich reactions such as $\bar{p}p$ annihilation, and radiative $J/\psi$ decay [13]. The spin of the $f_J(1710)$ is not yet confirmed, indications for both spin 2 and spin 0 have been reported. The glueballs are expected to be intrinsically unstable and decay in diverse ways, yielding typically two or more mesons. $f_J(1710)$ dominantly decays into $K^+K^-$ and $f_0(1500)$ into $\pi^+\pi^-\pi^+\pi^-$. One of the challenges in identifying a glueball state unambiguously lies in difficulties of isolating a glueball...
state from the conventional meson state that shares the same quantum numbers. To identify that the process is from DPE process rather than Reggeon exchange requires observing suppression of $\rho$ meson in the process, since $\rho$ cannot be formed from two states with $J^{PC} = 0^{++}$. The other “filter” for enhancing glueball candidates in DPE process is the “$\delta P_T$” filter [14], in which small momentum transfer processes enhance $gg$ kinematic configurations since the gluons can flow directly into the final state in the process. The technique for reconstructing resonances using the STAR detector system has been well established in $p+p$ and $A+A$ collisions. Especially the current ongoing central photo-production program in ultra-peripheral $AA$ collisions at STAR [15] is topologically similar to the DPE process, and the common experimental machinery can be utilized for triggering and analyzing DPE processes.

Figure 4 shows the expected reconstructed kinematic phase-space distributions of centrally produced mass decaying into $\pi^+\pi^-$ for 1M DPE events. Reconstruction of the tracks from decay was simulated using geometrical acceptance of the TPC ($-1 < y < 1$ with full azimuthal coverage) and particle identification by TPC and the Time-of-Flight system which can separate $\pi/K$ in momentum range up to 1.6 GeV/c. The effective mass range 1-3 GeV/$c^2$ are kinematically well accessible in pion and kaon decay channels. The high mass region is limited by particle identification and particles decaying outside of the rapidity coverage of TPC ($-1 < y < 1$). Expected trigger rates for DPE are 80 Hz at $1 \times 10^{32}$cm$^{-2}$s$^{-1}$. The two-Pomeron ($P\bar{P}$) cross-section at the RHIC energy is not known and estimates in Ref. [16, 17] are used. To collect ~100K $K^+K^-$ and ~250K $\pi^+\pi^-\pi^+\pi^-$ data sample (~75K, ~100K in $1 < M_X < 2$ GeV/$c^2$, respectively), it is estimated to require 2-3 weeks of RHIC running time reassuming branching ratios of DPE processes measured at $\sqrt{s} = 62.4$ GeV [15]. The assumed integrated luminosity can be easily achieved during the planned high luminosity spin program at RHIC in the future, and it’s expected that the luminosity upgrade and longer run can bring an order of magnitude higher statistics which will enable differential kinematic sampling and spin-parity analysis. The Odderon state can also be identified by studying centrally produced $C = -1$ diffractive vector mesons such as $J/\psi$ produced by Odderon-Pomeron coupling mixed with the photon-Pomeron coupling in inelastic diffractive collisions [19]. The measurement is expected to be deliverable by the STAR detector upgrade for optimized measurements for $J/\psi$ and high luminosity running even though the expected cross-section for diffractive $J/\psi$ at the RHIC energy is small [20].

5 Summary

A new rich diffractive physics program in polarized $p + p$ at RHIC with tagged forward protons using the Roman Pot technique with the STAR detector system has been launched. The unique machine and detector capabilities enable us to explore an important aspect of our understanding of the strong interaction. The main physics motivation is to search for theoretically predicted states in QCD: the Odderon and the glueball. The diffractive program, together with the other RHIC physics programs, will serve as an important role toward our complete understanding of the strong interaction and quantum chromodynamical description of the hadronic structure.
References

[1] Slides:
http://indico.cern.ch/materialDisplay.py?contribId=228&sessionId=19&materialId=slides&confId=53294

[2] For a review, see S. Donnachie et al., “Pomeron Physics and QCD”, Cambridge University Press (1999), and V. Barone and E. Predazzi, “High-Energy Particle Diffraction” Springer (2002).

[3] U. Amaldi et al., Phys. Lett. 44B, 112 (1973).

[4] S. Bultmann et al., Phys. Lett. B647, 88 (2007).

[5] K.H. Ackermann et al., Nucl. Instr. and Meth. A499, 624 (2003).

[6] E. Leader and T.L. Trueman, Phys. Rev. D61, 077504 (2000).

[7] E. Leader and R. Slansky, Phys. Rev. 148, 1491 (1966).

[8] N.H. Buttimore et al., Phys. Rev. D59, 114010 (1999).

[9] M. Bozzo et al., Phys. Lett. 155B, 197 (1985).

[10] M. Islam et al., Mod. Phys. Lett. A18, 743 (2003).

[11] For a review, see F.E. Close, Rep. Prog. Phys. 51, 833 (1988), and C. Amsler and N.A. Tornqvist, Phys. Rept. 389, 61 (2004).

[12] S. Abatziz et al., Phys. Lett. B324, 509 (1994).

[13] V. Crede and C.A. Meyer, Prog. Part. Nucl. Phys. 63, 74 (2009).

[14] F.E. Close and A. Kirk, Phys. Lett. B397, 333 (1990).

[15] B.I. Abelev et al., Phys. Rev. Lett. 102, 112301 (2009).

[16] K.H. Streng, Phys. Lett. B166, 443 (1986).

[17] Yu.A. Simonov, Phys. Lett. B249, 514 (1990).

[18] A. Breakstone et al., Z. Phys. C42, 387 (1989).

[19] A. Bzdak et al., Phys. Rev. D75, 094023 (2007).

[20] S. Klein and J. Nystrand, Phys. Rev. Lett. 92, 142003 (2004).