Study of nucleon structure using hadron beam at J-PARC

Natsuki Tomida[1,2,*]

[1]Center for Science Adventure and Collaborative Research Advancement (SACRA), Kyoto University, Kyoto 606-8502, Japan

[2]Department of Physics, Kyoto University, Kyoto 606-8502, Japan

Abstract. Recently, 30-GeV proton beam became available at the high momentum beamline of the J-PARC Hadron Experimental Facility. A following project of beamline upgrade will make available negative and positive secondary $\pi/K/p$ beam up to 20 GeV/c. We will study the nucleon partonic structure utilizing the high-momentum hadron beams. The generalized parton distributions (GPDs) of nucleon can be accessed by various single diffractive hard exclusive processes (SDHEPs): a pure hadronic process ($p + p \rightarrow p + \pi + B$), a diphoton production process ($\pi^- + p \rightarrow \gamma + \gamma + n$), and an exclusive Drell-Yan process ($\pi^- + p \rightarrow \mu^+ + \mu^- + n$). Measurements of these reactions give complementary information of nucleon GPDs to one from lepton-induced exclusive reactions.

1 Introduction

Although the standard model has been well established, there are many unknowns about the composite particles of quarks and gluons; namely hadrons. For example, a comprehensive understanding of mass and spin of the nucleon based on its partonic components is missing. The generalized parton distributions (GPDs) of the nucleon provides the information of multi-dimensional distributions of its partons [1, 2]. The second moments of GPDs yield the gravitational form factors and total angular momentum of partons. These information will help to access the origin of mass and spin of hadrons [1, 2]. There are four nucleon GPDs; $H, E, \tilde{H}$ and $\tilde{E}$, related with processes without a parton helicity flip. H and E are unpolarized GPDs, and $\tilde{H}$ and $\tilde{E}$ are polarized ones. GPDs are described as a function of x, ξ and t, which indicate the average momentum fraction carried by the struck parton, the fraction of longitudinal momentum fraction transferred to the struck parton, and the squared four momentum transfer, respectively.

GPDs can be accessed via measurements of hard exclusive reactions. There have been measurements of Deeply Virtual Compton Scattering (DVCS), Deeply Virtual Meson Production (DVMP) reactions and Timelike Compton scattering (TCS), utilizing high-luminosity lepton and gamma beams [3]. We plan to measure GPDs with novel hadron induced reactions at the high momentum beamline of J-PARC. These reactions are categorized as single diffractive hard exclusive processes (SDHEPs) [4, 5]; a pure hadronic process ($p + p \rightarrow p + \pi + B$) [6], a diphoton production process ($\pi^- + p \rightarrow \gamma + \gamma + n$) [7], and an exclusive Drell-Yan process

*e-mail: tomida.natsuki.5z@kyoto-u.ac.jp

($\pi^- + p \to \mu^+ + \mu^- + n$) [7–10]. Via measurement of these reactions, we can access the x-dependence of GPDs in the Efremov-Radyushkin-Brodsky-Lepage (ERBL) and Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) regions. These measurements are complementary to those with the lepton beams.

2 Experimental setup

At J-PARC, there is a proton synchrotron with a maximum beam energy of 30 GeV. There are several secondary beamlines in the Hadron Experimental Facility (HEF). At the HEF, the high momentum ("high-p") beamline, which delivers 30-GeV primary protons from the Main Ring with an intensity of 10^{10}/spill, has been constructed recently. The spill duration is 2.0 sec and the repetition cycle is 5.2 sec.

In addition, high momentum secondary beam will be delivered by installing a production target at the branching point of the high-p beamline [11]. The secondary beamline to construct is called π20 beamline. At the π20 beamline, negative and positive $\pi/K/p$ beam with 2-20 GeV/c will be delivered. The intensity of beam varies depending on particle and momentum. The maximum intensity will be 10^8/spill for π^- and 10^6/spill for K^- [12]. The beam momentum is to be measured using a Focal Plane Fiber Tracker (FPFT) with a resolution of $\Delta p/p$=0.1%. Unseparated beam will be delivered and identification of beam particle will be performed by a beam Ring Imaging Cherenkov (bRICH) detector.

At the π20 beamline, a multi purpose spectrometer will be installed. The schematic drawing of the spectrometer is shown in Fig.1. It consists of a FM magnet with the field strength of 1 T. Two Beam Fiber Trackers (BFT) measure tracks of charged beam particles. The tracks of scatted particles are measured with two Scatter Fiber Trackers (SFT) and four Drift Chambers (DC). The produced particles are identified with time-of-flight (TOF), threshold type Aerogel Cherenkov (AC), Ring Imaging Cherenkov (RICH) detectors and a muon identification system [13]. The TOF detectors consist of T0 [14], Multi-gap Resistive Plate Chambers (MRPCs) [15] and scintillating detectors [16]. The muon ID system consists of TOF-tracker MRPCs and a hadron absorber[13]. Streaming system will be used for data acquisition [17].

3 GPDs measurement at J-PARC

3.1 Pure hadronic process

Probing GPDs with a pure hadronic reaction was suggested by S. Kumano *et al.* in Ref.[6]. The proposed reaction is $N + N \to N + \pi + B$ shown in Fig.2, where N indicate a nucleon and B can be a nucleon or Δ. The N and π in the final state are required to possess large and nearly opposite transverse momenta. The large invariant mass of the $N\pi$ pair is essential to validate a dominance of small-size configuration of this reaction. The mandelstam variables s', t', u' are defined as $s' = (p_\pi + p_{N_{scattered}})^2$, $t' = (p_{N_{beam}} - p_{N_{scattered}})^2$ and $u' = (p_{N_{beam}} + p_\pi)^2$, respectively, where p denotes the momentum of the corresponding particle. The cross section of this reaction can be factorized into GPD and hadron scattering parts in the kinematical region $|s'|, |t'|, |u'| \gg m_N^2$ with $t'/s' = const$.

Probing GPDs with this process is very unique because this process can access the kinematical region $-\xi < x < \xi$ which is called ERBL region. The GPDs in this region can not be accessed via lepton induced reactions. Hence, this measurement gives unique information of GPDs complementary to lepton induced reactions. Moreover, we can access the x-dependence of GPDs which also cannot be accessed with the lepton induced reactions. The proposed reactions in Ref.[6] are (i)$p + p \to p + \pi^+ + n$, (ii)$p + p \to p + \pi^+ + \Delta^0$, and (iii)

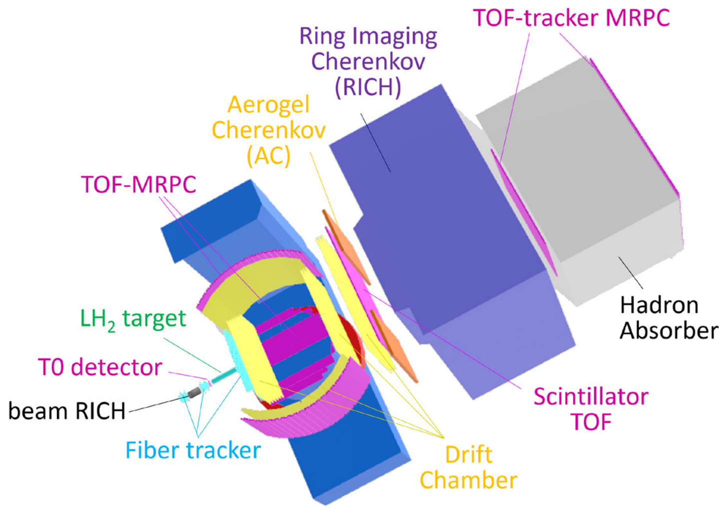

Figure 1. The schematic drawing of the spectrometer for the $\pi 20$ beamline.

$p + p \to p + \pi^- + \Delta^{++}$. The $N \to \Delta$ transition GPDs can be accessed with the reaction (ii) and (iii).

From the experimental perspective, the largest advantage of this reaction is the large cross section because of a hadronic reaction. The estimated differential cross section in Ref.[6] is a few μb/GeV^4. Measurement of this reaction can be done in the early stage experiment at the J-PARC high momentum beamline.

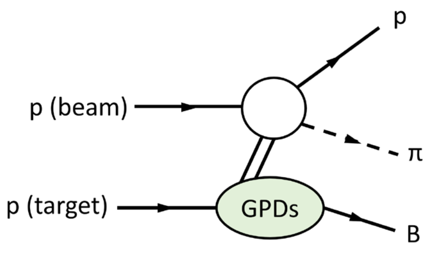

Figure 2. The pure hadronic $p + p \to p + \pi + B$ process.

3.2 Diphoton production processes

The extraction of GPDs from the diphoton production process ($\pi^- + p \to \gamma + \gamma + n$) is recently studied by J.-W. Qiu and Z. Yu in Ref.[7]. They argued that the scattering amplitude of this reaction can be factorized when photons have back-to-back high transverse momenta. They show that this process has enhanced sensitivity of the x-dependence of GPDs in the DGLAP region ($-1 < x < \xi$ or $\xi < x < 1$) near $x = \pm\xi$. The estimated cross section at the J-PARC beam energy is a few tenth pb/GeV^3[7]. To carry out the measurement, the γ detector, which is not included in the current spectrometer, should be added.

3.3 Exclusive Drell-Yan process

The exclusive Drell-Yan reaction is the time-reversal reaction of the Deeply Virtual Meson Production (DVMP). We can access GPDs from the cross section measurement of the exclusive Drell-Yan reaction [7–10]. Using π^- beam of the π20 beamline, we measure the $\pi^- + p \to \mu^+ + \mu^- + n$ reaction. We place the muon identification system consisting of tracking detectors and hadron absorbers at the most downstream of the spectrometer as shown in Fig.1. We measure momentum of dimuons using tracking detectors, located at the upstream of the hadron absorber and examine missing mass of the $\pi^- + p \to \mu^+ + \mu^- + X$ reaction. The missing-mass resolution is good enough to differentiate the exclusive Drell-Yan ($X = n$) processes and the inclusive ones [10]. The feasibility study for the experiment at the π20 beamline is described in Ref.[10]. The estimated cross section is a few - a few tenth pb/GeV^3 [7–10].

4 Summary

In J-PARC, 30 GeV proton beam became available and secondary $\pi/K/p$ beam up to 20 GeV/c will be available. Those high-momentum hadron beams can be used for exploring the nucleon GPDs in several novel reactions. We plan to measure single diffractive hard exclusive processes (SDHEPs), which are a pure hadronic process ($p + p \to p + \pi + B$), a diphoton production process ($\pi^- + p \to \gamma + \gamma + n$), and an exclusive Drell-Yan process ($\pi^- + p \to \mu^+ + \mu^- + n$). From the measurement of these reactions, we can access the x-dependence of GPDs in the ERBL and DGLAP regions. These measurements give complementary information to the measurement of lepton induced reactions.

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References

[1] M. Diehl, Physics Reports **388**, 41 (2003)
[2] X. Ji, Annual Review of Nuclear and Particle Science **54**, 413 (2004)
[3] S. Diehl, Progress in Particle and Nuclear Physics **133**, 104069 (2023)
[4] J.W. Qiu, Z. Yu, Phys. Rev. D **107**, 014007 (2023)
[5] J.W. Qiu, Z. Yu, JHEP **08**, 103 (2022)
[6] S. Kumano, M. Strikman, K. Sudoh, Phys. Rev. D **80**, 074003 (2009)
[7] J.W. Qiu, Z. Yu (2024), 2401.13207
[8] E. Berger, M. Diehl, B. Pire, Physics Letters B **523**, 265 (2001)

[9] S. Goloskokov, P. Kroll, Physics Letters B **748**, 323 (2015)

[10] T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, K. Tanaka, Phys. Rev. D **93**, 114034 (2016)

[11] K. Aoki et al., *Extension of the J-PARC Hadron Experimental Facility: Third White Paper* (2021)

[12] K. Shirotori et al., J-PARC P93 Proposal (2021)

[13] R. Uda, F. Hayashi, N. Tomida, W.C. Chang, M.L. Chu, C.Y. Hsieh, P.J. Lin, K. Miyamoto, H. Noumi, A. Sakaguchi et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1056**, 168580 (2023)

[14] K. Shirotori, T. Akaishi, RCNP Annual Report 2019 (2020)

[15] N. Tomida, F. Hayashi, W.C. Chang, M.L. Chu, M. Friend, C.Y. Hsieh, H. Noumi, A. Sakaguchi, H. Sako, K. Shirotori et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1056**, 168581 (2023)

[16] T. Ishikawa, M. Miyabe, H. Noumi, H. Ohnishi, Y. Sada, K. Shirotori, A.O. Tokiyasu, C. Yoshida, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1039**, 167164 (2022)

[17] R. Honda, T. Aramaki, H. Asano, T. Akaishi, W.C. Chang, Y. Igarashi, T. Ishikawa, S. Kajikawa, Y. Ma, K. Nagai et al., Progress of Theoretical and Experimental Physics **2021**, 123H01 (2021)