Subnuclear System Research Division
Radiation Laboratory

1. Abstract

Nucleons, such as protons and neutrons, are a bound state of constituent quarks glued together with gluons. The detail structure of nucleons, however, is not well understood yet. Especially the mechanism to build up the spin of proton, which is 1/2, is a major problem in physics of the strong force. The research goal of Radiation Laboratory is to solve this fundamental question using the world first polarized-proton collider, realized at RHIC in Brookhaven National Laboratory (BNL) in USA. RHIC stands for Relativistic Heavy Ion Collider, aiming also to create Quark Gluon Plasma, the state of Universe just after the Big Bang, and study its property. RIKEN-BNL Research Center (RBRC) also directed by H. En'yo carries our core team at BNL for those exciting researches using the PHENIX detector and its upgraded sPHENIX detector in preparation. We have observed that the proton spin carried by gluons is finite and indeed sizable. We also identified W bosons in the electron/positron decay channel and in the muon decay channel, with which we showed how much anti-quarks carry the proton spin. Other than the activities at RHIC we are preparing and starting new experiments at J-PARC and Fermilab to study the nature of hadron and preparing for the electron-ion collider (EIC). We are also performing technical developments such as novel ion sources, fine-pitch silicon pixel detectors and high-performance trigger electronics.

2. Major Research Subjects

(1) Spin physics with relativistic polarized-proton collisions at RHIC
(2) Study of nuclear matter at high temperature and/or at high density
(3) Technical developments on radiation detectors and accelerators

3. Summary of Research Activity

(1) Experimental study of spin structure of proton using RHIC polarized proton collider

[See also RIKEN-BNL Research Center Experimental Group for the activities at BNL]

The previously published central rapidity neutral and charged pion double spin asymmetries at the highest collision energies at RHIC of 510 GeV have been augmented with the world's first preliminary direct photon results. The direct photon probe also restricts the initial, hard interaction to be predominantly between a quark and a gluon thus further increasing the sensitivity to the gluon spin. It has therefore been considered the golden channel to access the gluon spin, albeit the statistics are limited. Also, the first preliminary jet results have been extracted by PHENIX. The jet measurement is in principle a cleaner probe since no fragmentation functions are involved as in the pion results. All these results will be included in future global fits of all the existing experimental data in the world and will improve the sensitivity of quark and gluon spin contributions to the total spin of the nucleon.

While orbital angular momentum cannot be directly accessed at RHIC, several transverse spin phenomena have been observed which relate to orbital angular momentum and the three-dimensional structure of the nucleon. These phenomena by themselves have become a major field of research as the dynamics of the strong interaction can be studies with these functions. Various single spin asymmetry measurements have been obtained for various rapidities. When moving to central rapidities, these left-right asymmetries are known to be very small for neutral pions. Since then, they have been confirmed to be small also for eta mesons. A substantially improved data set with significantly reduced uncertainties has been recently published in PRD for both final states. For the first time also direct photon single spin asymmetries have been extracted at RHIC. The direct photon asymmetries are again very important here as they are only sensitive to the transverse spin effects in the initial state and not the fragmentation-related effects. Furthermore, it provides sensitivity to a gluon correlation function that is not accessible in other processes. The direct photon results have also been submitted for publication in PRL.

In June of 2017, an electro-magnetic calorimeter was installed in the most forward area of the STAR experiment and took polarized proton collision data for neutral particle production (neutron, photon, neutral pion). The cross-section measurement will give us new inputs to develop high-energy particle-collision models which are essential to understand air-shower from ultra-high energy cosmic rays. The asymmetry measurement will improve the understanding of hadronic collisions at small scales. An unexpectedly large neutral pion asymmetry has been found using this data that may connect to the large pion asymmetries at smaller rapidities and higher transverse momenta. The results have been published in PRL.

At similar rapidities also neutron asymmetries have been observed in the past. While previously only their general magnitude was obtained, using unfolding techniques it was possible to extract the first asymmetries as a function of the neutron transverse moment for proton-proton collisions. These results have been published in PRD and correlated asymmetries, as well as asymmetries in proton-nucleus collisions are being prepared.

Some of us are participating in the Fermilab SeaQuest experiment as a pilot measurement of muon pairs from Drell-Yan process using a 120-GeV unpolarized proton at Fermilab. After finishing unpolarized measurements in 2017 to study the quark spin-orbit effect, a new measurement with a polarized proton target will start in 2021 to study the sea-quark orbit effect of the polarized proton in the target. The first result from the SeaQuest experiment on the asymmetry of the antimatter in the proton has been recently published in Nature.

For many jet related measurements fragmentation functions are necessary to gain spin and or flavor sensitivity. Those are currently extracted by some of us using the KEK-Belle data. In addition to using the fragmentation results with RHIC measurements, they will also provide the basis for most of the key measurements to be performed at the electron-ion collider. In 2020, in improved result for single and di-hadron fragmentation in different event topologies was published in PRD. These measurements are essential to nearly all nucleon structure measurements at RHIC, semi-inclusive DIS and the EIC.

As the Electron-Ion Collider is becoming a reality, many of us are participating in the various community efforts to define the physics goals of the EIC and how they inform on the choices of collisions energies, luminosities, and detector components. While the accelerator efforts are naturally led by the two main nuclear physics laboratories in the US, BNL and JLAB, a large EIC user group of more than 1200 members from all around the world is working on making the EIC a reality. Within this group, we are participating in various functions from the steering committee, the conference and talks committee to various physics or detector related topical groups. During 2020 the community effort leading to the so-called Yellow Report studied and summarized these physics and detector requirements in detail and the Yellow Report has since been made public on the arXiv.

(2) Experimental study of quark-gluon plasma using RHIC heavy ion collider

[See also RIKEN-BNL Research Center Experimental Group for the activities at BNL]

We have completed several key measurements in the study of quark-gluon plasma at RHIC. As the top of them, we lead the analysis of the first thermal photon measurement in heavy ion collisions. The measurement indicates that the initial temperature reached in the central Au + Au collision at 200 GeV is about 350 MeV, far above the expected transition temperature $T_c \sim 170$ MeV, from hadronic phase to quark-gluon plasma. This work was rewarded by Nishina Memorial Prize given to Y. Akiba in 2011. We also measured direct photons in d + Au and direct photon flow strength v_2 and v_3 in Au + Au

We led measurement of heavy quark (charm and bottom) using VTX, a 4-layer silicon vertex tracker which we jointly constructed with US DOE. The detector was installed in PHENIX in 2011. PHENIX recorded approximately 10 times more data of Au + Au collisions in the 2014 run than the 2011 run. PHENIX recorded high statistics $p + p$ and $p + A$ data in 2015, and the doubled the Au + Au in 2016. PHENIX concluded its data taking in the 2016 run.

The results of the 2011 run were published in Physical Review C (Phys. Rev. C **93**, 034904 (2016)). This is the first publication from VTX. The result showed that the electrons from bottom quark decay is suppressed for $p_T > 4$ GeV/c, but the suppression factor is smaller than that of charm decay electrons for $3 < p_T < 4$ GeV/c. This is the first observation of bottom electron suppression in heavy ion collisions, and the first result that shows the bottom and charm suppression is different. The results of $b \to e$ and $c \to e$ measurement in the 2015 $p + p$ run has been published in Physical Review D99, 092003 (2019). The centrality dependence of the suppression $b \to e$ and $c \to e$ from the 2014 Au + Au data is in preparation. The 2016 run is the final data taking run of PHENIX, and this run doubled the dataset for heavy-flavor measurement with VTX. This year we completed the VTX geometry calibration of the 2016 run.

PHENIX published measurements of flow strength in p + Au, d + Au, and ^{3}He + Au (Nat. Phys. **15**, 214 (2019)). The results provide strong evidence for formation of small droplet of quark gluon plasma in collisions of small systems at RHIC.

In Wako we are operating a cluster computer system (CCJ) specialized to analyze huge data sets taken with the PHENIX detector. It consists of 28 nodes (18 old nodes and 10 new nodes) each of which has two CPUs and 10 sets of local disks for data repository (old node: quad-core CPU, 1 TB disk, new node: six-core CPU, 2 TB disk). There are 264 CPU cores and 380 TB disks in total. This configuration ensures the fastest disk I/O when each job is assigned to the node where the required data sets are stored. It is also important that this scheme does not require an expensive RAID system and network. Through this development we have established a fast and cost-effective solution in analyzing massive data.

The data of 0.9 PByte obtained by the PHENIX experiment is stored in a hierarchical storage system which is a part of HOKUSAI BigWaterfall/SailingShip supercomputer systems operated by the Head Office for Information Systems and Cybersecurity. In addition, we operate a dedicated server for the RHICf group and two servers for the J-PARC E16 group, to keep their dedicated compilation and library environments, and some data.

(3) Study of properties of mesons and exotic hadrons with domestic accelerators

Preparation of the experiment E16 at J-PARC Hadron experimental facility is underway with several Grant-in-Aids. This experiment aims to perform a systematic study of the spectral modification of low-mass vector mesons in nuclei to explore the physics of chiral symmetry breaking and restoration in dense nuclear matter, namely, the mechanism proposed by Nambu to generate most of hadron masses.

The Gas Electron Multiplier (GEM) technology is adopted for the two key detectors, GEM Tracker (GTR) and Hadron-blind Cherenkov detector (HBD). To improve electron-identification performance, lead-glass calorimeters (LG) are used in combination with HBD. We are in the production phase. Read-out electronics and trigger logic modules are also installed and tested. We have been a member of the CERN-RD51 collaboration to acquire the read-out technology for GEM. The MoU for RD51 was extended for the period of 2019–2023.

Due to the budgetary limitation, we aim to install a part of the detectors at the beginning of the experiment, eight modules of a set of GTR, HBD and LG, out of 26 modules in the full installation. J-PARC PAC (Program Advisory Committee) gave us a stage-2 approval in July 2017 to perform commissioning runs (Run 0). Although there is a significant delay from the originally planned date of March 2016, the construction of the beam line by KEK was completed finally in early 2020 to perform this experiment.

We performed the 1st half of commissioning run (Run-0a) in June 2020 successfully, using a primary proton beam with an intensity of 1×10^{10} protons per 2-sec duration of beam spill. This intensity is a designed full intensity of the beam line. The 2nd half, which started in February 2021, was suspended due to the malfunction of the J-PARC MR accelerator and a compensation beam time is allocated in June 2021. Eight modules of GTR, six modules of HBD and six modules of LG are assembled and installed in the E16 spectrometer magnet in January 2021 for this beam time. First physics run is planned in JFY2022, after two more HBDs and two more LG modules are installed.

(4) Detector development for PHENIX experiment

The PHENIX experiment proposes substantial detector upgrades to go along the expected accelerator improvements, including the future electron-ion collider "EIC." The present PHENIX detector is repurposed to the sPHENIX (super PHENIX) detector which reuses the Babar solenoid magnet at SLAC and is covered by the hadronic calorimeter which was not available in the previous RHIC experiments. The sPHENIX was approved for the Project Decision-2/3 (corresponds to DOE's Critical Decision-2/3) in May 2019. We RIKEN group have been developing the one of the tracking devices of sPHENIX detector, so called intermediate tracker (INTT) since 2015. The INTT provides the best timing resolution among the sPHENIX tracking system, in conjunction with a time projection chamber and a MAPS based vertex detectors. The prototype detectors demonstrated satisfactory performance in the efficiency and position resolutions as designed in the last two beam tests at the Fermilab Test Beam Facility (FTBF) using 120 GeV proton beam in March 2018 and June 2019. The production of silicon ladder assembly has been proceeded both in Taiwan Silicon Detector Facility (TSiDF) and BNL since Spring 2021. The INTT barrel assembly will be started in this Summer.

We have been planning to build a forward spectrometer to be added to the sPHENIX detector. With this addition, the detector called fsPHENIX will have hadronic and electromagnetic calorimetry as well as tracking capability in the forward rapidity region. This upgrade makes it possible to study forward jets and hadrons in jets which are of vital importance for the cold QCD program in polarized $p+p$ and $p+A$ collisions at RHIC. The fsPHENIX detector can be further upgraded to the ePHENIX detector to be used for electron-ion collisions at EIC. We are preparing test bench to perform R&D for the forward hadron calorimeter.

As the further investigation of the neutral pion production asymmetry discovered in the RHICf experiment, we started preparation for the next phase of the experiment, namely RHICf-II. The target year of physics data taking is 2024 as a part of either STASR or sPHENIX experiments. The highlight of the upgraded experiment is to adopt a larger acceptance with higher position resolution for the zero-degree calorimeter (ZDC). The detector technology developed for the FoCAL upgrade project of the ALICE experiment at LHC well satisfies the RHICf-II performance requirement. We thus resumed the associated membership of the ALICE collaboration, and the RHICf-II detectors are to be developed together with the ALICE FoCAL collaboration. This new detector technology development is also a part of an essential R&D programs for a ZDC detector for EIC.

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List of Publications & Presentations

Publications

[Original Papers]

U. A. Acharya *et al.* (PHENIX Collaboration), "Transverse single-spin asymmetries of midrapidity π^0 and η mesons in polarized $p+p$ collisions at $\sqrt{s} = 200$ GeV," Phys. Rev. D **103**, 5, 052009 (2021).

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U. A. Acharya *et al.* (PHENIX Collaboration), "Polarization and cross section of midrapidity J/ψ production in $p+p$ collisions at $\sqrt{s} = 510$ GeV," Phys. Rev. D **102**, 7, 072008 (2020).

U. A. Acharya *et al.* (PHENIX Collaboration), "Production of $b\bar{b}$ at forward rapidity in $p+p$ collisions at $\sqrt{s} = 510$ GeV," Phys. Rev. D **102**, 9, 092002 (2020).

U. A. Acharya *et al.* (PHENIX Collaboration), "Measurement of jet-medium interactions via direct photon-hadron correlations in Au + Au and d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **102**, 5, 054910 (2020).

U. A. Acharya *et al.* (PHENIX Collaboration), "Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p+p$ collisions at $\sqrt{s} = 510$ GeV," Phys. Rev. D **102**, 3, 032001 (2020).

L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato, and R. Seidl, "Electron-Ion Collider impact study on the tensor charge of the nucleon," Phys. Lett. B **816**, 136255 (2021).

R. Seidl, *et al.* (Belle Collaboration), "Update of inclusive cross sections of single and pairs of identified light charged hadrons," Phys. Rev. D **101**, 092004 (2020).

J. Dove, Y. Goto, *et al.*, "The asymmetry of antimatter in the proton," Nature **590**, 561–565 (2021).

Presentations

[International Conferences/Workshops]

K. Kanno (invited), "Experimental study of spectral change of vector mesons in nuclear medium at J-PARC," YITP international workshop on Hadron in Nucleus (HIN2020), Kyoto (YITP), Japan & Online, March 8–10, 2021.

T. N. Takahashi (poster), "Data acquisition system in Run0 of the J-PARC E16 experiment," 22nd IEEE Real Time Conference (RT2020), Online, October 12–23, 2020.

R. Seidl (invited), "PHENIX highlights," RHIC AGS Users Meeting 2020, October 23, 2020.

R. Seidl (invited), "Fragmentation related measurements at Belle," 40th International Conference on High Energy Physics (ICHEP 2020), Prague, July 31, 2020.

Y. Goto, "Physics and detector requirements at zero degree of EIC," Contribution to: Workshop of QCD and Forward Physics at the Future Electron Ion Collider and Cosmic Ray Physics, 59–64 (2020).

K. Sato, Y. Goto, I. Nakagawa, R. Seidl, J. S. Park, M. H. Kim, *et al.*, "The energy spectrum of forward photons measured by the RHICf experiment in $\sqrt{s} = 510$ GeV proton-proton collisions," PoS **ICRC2019**, 413 (2021).

Benard Mulilo, "Transverse momentum dependent forward neutron single spin asymmetry in $p+p$ collisions at 200 GeV," International Workshop on Forward Physics and QCD with LHC, EIC and Cosmic Rays, held at JLAB January 20–23, 2021.

Benard Mulilo, "PHENIX preliminary results of forward neutron transverse single spin asymmetry in $p^{\uparrow}+p$ collisions at $\sqrt{s} = 200$ GeV," IWHSS2020 Conference, Trieste-Italy, November 16, 2020.

[Domestic Conferences/Workshops]

四日市悟 (招待講演), 「DAQ and circuit in the J-PARC E16 experiment」, 計測システム研究会 2020, 茨城県東海村/オンライン開催, 2020 年 11 月 26–27 日.

中須賀さとみ (口頭発表), 「J-PARC E16 実験のための電子識別検出器の性能評価 II」, 日本物理学会 2020 年 秋季大会, オンライン開催, 2020 年 9 月 14–17 日.

近藤丈仁 (口頭発表), 「J-PARC E16 実験 GEM 飛跡検出器トリガ用信号読出回路の対放電保護」, 日本物理学会 第 76 回 年次大会, オンライン開催, 2021 年 3 月 12–15 日.

村上智紀 (口頭発表), 「J-PARC E16 実験における GEM 飛跡検出器の建設及び実機の性能評価」, 日本物理学会 第 76 回 年次大会, オンライン開催, 2021 年 3 月 12–15 日.

Ralf Seidl (invited), "RHIC and COMPASS results," 「日本のスピン物理学の展望」研究会, 島根県松江市, 2021 年 2 月 23–24 日.

Ralf Seidl (invited), “The electron ion collider as a next generation facility for the study of QCD,” KEK 研究会「素粒子・原子核コライダー物理の交点」, オンライン開催, 2020 年 8 月 31 日.

Y. Goto (invited), “FoCal, RHICf-II and EIC,” TCHoU Workshop, Online Meeting, March 30, 2021.

後藤雄二（口頭発表）,「PHENIX 実験での縦スピン非対称度測定の最新の結果」, 日本物理学会第 76 回年次大会, オンライン開催, 2021 年 3 月 13 日.

後藤雄二（招待講演）,「Electron-Ion Collider の物理」,「日本のスピン物理学の展望」研究会, 島根県松江市, 2021 年 2 月 23–24 日.

後藤雄二（招待講演）,「EIC 日本グループの議論」, KEK 研究会「素粒子・原子核コライダー物理の交点」, オンライン開催, 2020 年 8 月 31 日.

後藤雄二（口頭発表）,「$\sqrt{s}$ = 510 GeV での縦偏極陽子衝突による荷電パイ中間子の二重スピン非対称度の測定」, 日本物理学会 75 回年次大会, 愛知県名古屋市 (現地開催中止), 2020 年 3 月 17 日.

[Seminars]

Ralf Seidl (invited), “Fragmentation function measurements in Belle,” Hiroshima University Nuclear and Particle Physics Seminar, September 3, 2020.

Press Releases

「陽子の中の反物質が持つ大きな非対称性の発見—反クォークの生成過程により物質の成り立ちを探る—」, 東京工業大学, 高エネルギー加速器研究機構, 山形大学, 理化学研究所, 2021 年 2 月 25 日.