Subnuclear System Research Division
Radiation Laboratory

1. Abstract

When Yoshio Nishina passed away in 1951, the research activities in Nishina's Laboratory in RIKEN were inherited by three laboratories, and Radiation Laboratory is the one of them. The Radiation Laboratory, whose legacy has been kept for 64 years, lead by F. Yamazaki, T. Hamada, M. Ishihara and last 21 years by H. En'yo, is closed in March 2022. In the last 28 years, we have proposed and built a polarized proton collider at RHIC, Relativistic Heavy Ion Collider at Brookhaven National Laboratory in the USA, and discovered that gluons in the proton carry a sizable portion of the proton spin which is 1/2. 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. We were successful at RHIC to create Quark Gluon Plasma, the state of Universe just after the Big Bang. Such creation was confirmed through the many interesting discoveries such as "Jet Quenching," "Elliptic Particle Flows," "Thermal Photon Radiation" and so on. The RIKEN-CCJ, Linux-based Computer Cluster in Japan, was firstly built in Japan and is still operational in our laboratory and lead many analyses towards those discoveries. We have discovered the first hint of the restoration of Chiral Symmetry Breaking, the mechanism to create 99% of our weight, through the observation of phi meson mass-modification in nuclear matter at the 12-GeV Proton Synchrotron in KEK. This program is now acceded by the E16 experiment in J-PARC.

On the course of those experiments, we have conducted handful of technical developments, which include laser-induced novel ion sources, helical snake magnets for RHIC and AGS, fine-pitch silicon pixel detectors for PHENIX and sPHENIX experiments, high-performance trigger electronics, gas-electron-multipliers for hadron-blind detectors and trackers. With some of those new developments, 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) yet to be built at BNL in near future.

The legacy of our laboratory is taken over by RIKEN-BNL Research Center (RBRC) in BNL and by the new laboratory "RHIC Physics Research Group" headed by Y. Akiba in RIKEN Nishina Center for Accelerator-Based Science.

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]

After the previously published central-rapidity neutral and charged pion double-spin asymmetries at the highest collision energies at RHIC of 510 GeV now also the world's first direct photon results have been brought to publication. 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 since the inception of the RHIC spin program more than two decades ago. Because of the electromagnetic interaction involved in the direct photon process the statistics are limited, compared to hadronic final states. Therefore, it took the largest polarized data set to finally be able to extract these double spin asymmetries. The results are found to be consistent with global fits of the previous hadron and jet measurements from RHIC as well as semi-inclusive DIS. 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 expectingly 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. A recently published measurement by PHENIX for charged pions at mid-rapidity shows also small asymmetries but at the same time also a hint of a charge separation. Such a charge separation could originate from a flavor dependence and could also explain the smallness of the neutral meson asymmetries where the effects from up and down quark flavors could cancel each other out.

For the first time also direct photon single spin asymmetries have been extracted at RHIC. The direct photon asymmetries are again 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 been published in PRL.

In June of 2017, an electro-magnetic calorimeter, RHICf, 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 first photon cross section measurements at very forward rapidities have recently been submitted for publication.

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. The RHICf results have followed up these PHENIX results and, after confirming the consistency at small transverse momenta, extended the transverse momentum range significantly. These results are currently being prepared for publication. Similar PHENIX neutron asymmetries in proton-nucleus collisions have been analyzed as a function of both transverse and longitudinal momenta, as well as in (anti)correlation with hadronic detector activity elsewhere. These results have been published in PRD and clearly show the interplay between hadronic interactions that predominantly produce negative asymmetries and ultra-peripheral collisions that produce positive asymmetries and gain in relevance with heavier nuclei.

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 2022 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 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 2021, a new fragmentation analysis of predominantly vector mesons and D mesons decaying into two or three light hadrons has been prepared and is in the process of being finalized. All 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. During 2021, the first detector proposals were prepared with the selection of the first EIC detector by an external committee. The first detector is part of the DOE based EIC project. Given the participation in the sPHENIX experiment, we participated heavily in the ECCE proposal that also revolves around reusing the BABAR/sPHENIX magnet. We were leading the inclusive and semi-inclusive physics studies that showed the feasibility of the main EIC goals with such a detector. Others participated strongly in the detector considerations for an ECCE zero-degree calorimeter. At the end of 2021 the ECCE proposal was unanimously selected as the first EIC detector and is currently being prepared to form an actual collaboration.

(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. A paper reporting the results of $b \to e$ and $c \to e$ measurement in the 2015 $p + p$ run has been published in Phys. Rev. D **99**, 092003 (2019). The centrality dependence of the suppression $b \to e$ and $c \to e$ from the 2014 Au+Au data has been submitted for publication. The results show clear quark mass dependence of energy loss in the QGP produced at RHIC. The 2016 run is the final data taking run of PHENIX, and this run doubled the dataset for heavy-flavor measurement with VTX. The production of nDSTs of the 2016 VTX data is completed and they are ready for physics analysis.

PHENIX published measurements of flow strength in p + Au, d + Au, and ^{3}He+Au (Nature Physics **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 25 nodes (17 old nodes and 8 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 1.1 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.

After the successful commissioning runs held in JFY 2020, we performed the second commissioning run in June 2021. Two-electron trigger to accumulate the data of vector meson decays were tested. The micro beam structures were newly found which deteriorates DAQ and trigger performances. Countermeasures for the structures were already discussed in cooperation with the accelerator group and Beam line group in J-PARC, and will be adopted in the coming beam time in the first quarter of 2023. On the other hand, detector performances were almost satisfied. In our plan, physics run will be performed in 2023–24, after the beam study. Approval of physics run will be discussed in PAC held in Summer 2022.

This activity is moved to Meson Science Laboratory after the closing of Radiation Laboratory.

(4) Detector development for PHENIX/sPHENIX 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 INTT silicon ladders have been demonstrated the satisfactory performance as designed through the three beam tests in 2018, 2019, and 2021 in Fermilab Test Beam Facility (FTBF) and Research Center for Electron Photon Science, Tohoku University. The production of silicon-ladder assembly was completed by Spring 2022 in the Taiwan Silicon Detector Facility (TSiDF) and in BNL. And the INTT barrel assembly has been started since June 2022 in BNL. The INTT barrel is scheduled to be installed to the beam line at the sPHENIX site in January 2023 followed by the sPHENIX commissioning in February 2023.

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. Since physics data taking at RHIC in 2024, which is required for RHICf-II, will not be implemented, we are considering other possibilities to achieve its physics goal. 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), "Improving constraints on gluon spin-momentum correlations in transversely polarized protons via midrapidity open-heavy-flavor electrons in $p\uparrow+p$ collisions at $\sqrt{s}$ = 200 GeV," e-Print: 2204.12899 [hep-ex], April 27, (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in p+p, p+Au d+Au, and ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," e-Print: 2203.09894 [nucl-ex], March 18, (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Study of ϕ-meson production in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Contribution to 2022 Snowmass Summer Study, e-Print:2203.06087 [nucl-ex], March 11, (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Measurement of direct-photon cross section and double-helicity asymmetry at $\sqrt{s}$ = 510 GeV in $\vec{p}+\vec{p}$ collisions," e-Print: 2202.08158 [hep-ex], February 16, (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Measurement of ψ (2S) nuclear modification at backward and forward rapidity in p+p, p+Al, and p+Au collisions at $\sqrt{s}$ = 200 GeV," e-Print: 2202.03863 [nucl-ex], February 8, (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Transverse-single-spin asymmetries of charged pions at midrapidity in transversely polarized p+p collisions at $\sqrt{s}$ = 200 GeV," Phys. Rev. D **105**, 032003 (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Systematic study of nuclear effects in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV using π^0 production," Phys. Rev. C **105**, 064902 (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Transverse single spin asymmetries of forward neutrons in p+p, p+Al and p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV as a function of transverse and longitudinal momenta," Phys. Rev. D **105**, 032004 (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Kinematic dependence of azimuthal anisotropies in p+Au, d+Au, and ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV, Phys. Rev. C **105**, 024901 (2022).

U. A. Acharya *et al*. (PHENIX Collaboration), "Probing gluon spin-momentum correlations in transversely polarized protons through midrapidity isolated direct photons in $p\uparrow+p$ collisions at $\sqrt{s}$ = 200 GeV," Phys. Rev. Lett. **127**, 162001 (2021).

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**, 052009 (2021).

U. A. Acharya *et al*. (PHENIX Collaboration), "Transverse momentum dependent forward neutron single spin asymmetries in transversely polarized p+p collisions at $\sqrt{s}$ = 200 GeV," Phys. Rev. D **103**, 032007 (2021).

O. Adriani *et al*. (RHICf Collaboration), "Performance of RHICf detector during operation in 2017," J. Instrum. **16**, P10027 (2021).

T. N. Takahashi *et al*., "Data acquisition system in the first commissioning run of the J-PARC E16 experiment," IEEE Trans. Nucl. Sci. **68**, 1907 (2021).

Presentations

[International Conferences/Workshops]

Y. Goto (invited), "Prospective physics study at EIC," 8th Asian Triangle Heavy-Ion Conference (ATHIC2021), Incheon, South Korea, Online, Novermber 9, 2021.

T. N. Murakami (poster), "Construction and operation of gas electron multiplier tracker for the J-PARC E16 experiment in run0," 2021 Virtual IEEE Nuclear Science Symposium, Online, October 16–23, 2021.

K. Kanno (invited), "Study of spectral change of vector mesons in nuclear medium at J-PARC," 2nd International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility, Online, February 16–18, 2022.

S. Yokkaichi (invited), "J-PARC E16 has started—spectral change of vector mesons in nuclei—," Reimei Workshop, "Hadrons in dense matter at J-PARC", Tokai, Japan, Hybrid, February 21–23, 2022.

S. Nakasuga (poster), "Commissioning of the electron identification system for dilepton measurement in pA collisions at J-PARC," VCI2022 (The 16th Vienna Conference on Instrumentation), Online, February 21–25, 2022.

[Domestic Conferences/Workshops]

後藤雄二（招待講演),「RHIC Spin Physics」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 17 日.

後藤雄二（口頭発表),「PHENIX 実験での $\sqrt{s_{NN}}$ = 200 GeV 偏極陽子＋原子核衝突による超前方中性子のシングルスピン非対称度の横運動量依存性」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 16 日.

高橋智則 (招待講演),「有限密度媒質中でのクォーク相関の解明に向けたレプトン対精密測定」, 第 6 回クラスター階層領域研究会, オンライン, 2021 年 6 月 14 日, 6 月 19 日.

高橋智則 (招待講演),「J-PARC E16 実験の計測システムの現状と課題」, 計測システム研究会 2021, 九州大学 (福岡市), ハイブリッド, 2021 年 10 月 28–29 日.

村上智紀,「J-PARC E16 実験 Run0 における GEM 飛跡検出器実機の性能評価」, 日本物理学会 第 77 回 年会, オンライン, 2022 年 3 月 15–19 日.

村上智紀,「J-PARC 高運動量ビームラインを用いた原子核密度中における ϕ 中間子質量スペクトルの測定」, J-PARC ハドロン研究会, オンライン, 2022 年 3 月 22–24 日.

[Seminars]

H. En'yo, "Forty academic years with physics of high density nuclear matter (in Japanese)," Heavy Ion Pub, Nagoya University, Online, November 12, 2021.

H. En'yo, "My 40 years seeking for the new phase of nuclear matter (in Japanese)," ELPH Seminar, Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, Japan, Hybrid, December 23, 2021.

Press Release

"Direct Photons Offer Glimpse of Gluons' Dynamic Motion—PHENIX data validate approach for future studies of proton spin and structure—," October 12, 2011. https://www.bnl.gov/newsroom/news.php?a=119077,https://www.riken.jp/press/2021/20211015_1/index.html.