Subnuclear System Research Division
RHIC Physics Research Laboratory

1. Abstract

RHIC Physics Research laboratory study the strong interaction with PHENIX and sPHENIX experiment at RHIC collider in Brookhaven National Laboratory in the U.S.A. This laboratory is formed in 2022 to be the RIKEN base of RIKEN BNL Research Center after the Radiation Laboratory was closed. The two physics goals of RHIC are (1) to study quark-gluon plasma produced in heavy ion collisions and (2) to study the spin structure of the proton. The second physics program has been promoted by RIKEN's leadership.

The aim of Heavy ion physics at RHIC is to re-create Quark Gluon Plasma (QGP), the state of Universe just after the Big Bang. Two important discoveries, jet quenching effect and strong elliptic flows, have established that new state of dense matter is indeed produced in heavy ion collisions at RHIC. RIKEN group has played a leading role in the study of QGP. In particular we achieved the first observation of thermal photons from QGP and estimated its initial temperature. The temperature is approximately 350 MeV, well above the transition temperature to QGP (~160 MeV).

The original goals of RHIC spin program are to measure the gluon spin contribution to the proton and to measure ani-quark polarization with the $W \to e$ and $W \to \mu$ measurement. rsults from PHENIX π^0 measurement and STAR jet measurement has shown that gluons in the proton carry about 30% of the proton spin. This is a major milestone of the RHIC spin program. The final results of $W \to e$ measurement was published in 2016 and the final results of $W \to \mu$ was published in 2018. The focus of the RHIC spin program is moved to study of transverse spin measurement.

PHENIX completed its data taking in 2016 to be upgraded a new experiment and detector, sPHENIX. sPHENIX will measure jets, photons, and Upsilon particles and will complete the scientific mission of RHIC. We constructed a intermediate-silicon tracker INTT for sPHENIX. INTT was completed in 2022 and it was installed in sPHENIX in March 2023. The sPHENIX will start taking data in 2023.

2. Major Research Subjects

(1) Experimental Studies of the Spin Structure of the Nucleon
(2) Study of Quark-Gluon Plasma at RHIC
(3) sPHENIX INTT detector

3. Summary of Research Activity

We study the strong interactions (QCD) using the RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized $p + p$ collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment. Y. Akiba (Laboratory Director) is the Spokesperson of PHENIX experiment since 2016.

Research Activity of this laboratory has large overlap with that of RBRC Experimental group since this laboratory is the RIKEN Wako campus base of RBRC. In the below, recent results reported in the report of RBRC experimental group is excluded.

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

How is the spin of proton formed with 3 quarks and gluons? This is a very fundamental question in Quantum Chromodynamics (QCD), the theory of the strong nuclear forces. The RHIC Spin Project has been established as an international collaboration between RIKEN and Brookhaven National Laboratory (BNL) to solve this problem by colliding two polarized protons for the first time in history. This project also has extended the physics capabilities of RHIC.

The first goal of the Spin Physics program at RHIC is to determine the gluon contribution to proton spin. It is known that the spin of quark accounts for only 25% of proton spin. The remaining 75% should be carried either by the spin of gluons or the orbital angular momentum of quarks and gluons. One of the main goals of the RHIC spin program has been to determine the gluon spin contribution. Before the start of RHIC, there was little experimental constraint on the gluon polarization, ΔG.

PHENIX measures the double helicity asymmetry (A_{LL}) of π^0 production to determine the gluon polarization. Our most recent publication of $\pi^0 A_{LL}$ measurement at 510 GeV shows non-zero value of A_{LL}, indicating that gluons in the proton is polarized. Global analysis shows that approximately 30% of proton spin is carried by gluon spin. PHENIX measured the parity-violating single spin asymmetry A_L of the W boson production in $p + p$ in wide rapidity range. The results of the W boson measurements were published in 2016 and 2018, and these results give constraints on the anti-quark polarization in the proton. The focus of the spin physics is now moved to the measurements of the single transverse spin asymmetry A_N.

In 2017, an electromagnetic calorimeter RHICf detector was installed in the most forward area of the STAR experiment to obtain polarized proton collision data for neutral particle production (neutrons, photons, neutral pions) as the RHICf experiment. In addition to the already obtained asymmetry of neutral pions, the analyses of the production cross section of photons and asymmetry of neutrons were almost completed and presented at international conferences and workshops. The photon production cross sections are compared with results from proton collisions at higher energies at the CERN-LHC, and the results support a scaling law that is independent of collision energy. These results provide new data necessary for the development of event generation codes to reproduce ultra-high energy cosmic ray collision events with the atmosphere. The data analysis of high statistics for neutron asymmetries has yielded results that cover a wide transverse momentum region with the expected high resolution, and the data are very interesting, showing large asymmetries. A theoretical study is also being conducted to investigate the origin of these asymmetries, and comparisons with experimental data are being made. The final results of both studies are being prepared for publication.

It is aiming to obtain physics data in 2024 to further elucidate the neutral production cross sections and asymmetries discovered by the RHICf experiment. Although this experiment has not yet been approved, it will use silicon detector technology developed in the ALICE-FoCal upgrade project at the LHC to introduce a larger detector with higher position resolution. Therefore, the collaboration with ALICE has been resumed as an associated member and the detector is being jointly developed with the FoCal group. The development of this new detector technology is also part of an essential R&D program for a zero-degree calorimeter (ZDC) detector for EIC. As a result of the fabrication of a prototype detector, its testing and evaluation in the laboratory, test beams at the ELPH facility at Tohoku University and the CERN-PS and SPS accelerators, and radiation tolerance tests at the RIKEN RANS neutron irradiation facility, the selection of silicon detector technology for the actual detector was almost completed and the next stage of detector fabrication is about to begin.

(2) Experimental study of Quark-Gluon Plasma using RHIC heavy-ion collider

The goal of high energy heavy ion physics at RHIC is study of QCD in extreme conditions *i.e.* at very high temperature and at very high energy density. Experimental results from RHIC have established that dense partonic matter is formed in Au + Au collisions at RHIC.

PHENIX completed its data taking after the 2016 run. We continue data analysis of PHENIX data. Recent highlights of study of QGP by PHENIX is presented in the report by RBRC experimental group.

(3) sPHENIX INTT detector

We constructed intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will start taking data in 2023. The INTT detector consists of 56 ladders, which are arranged to two layers of barrels. A ladder is shown in Fig. 1. It is a basic building block of the INTT.

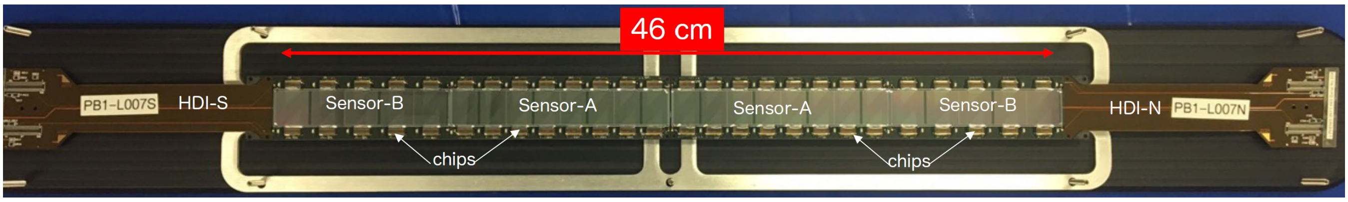

Fig. 1. Left: Completed two halves of INTT detector with members of INTT teams. Right: INTT detector and INTT team just after installation to sPHENIX.

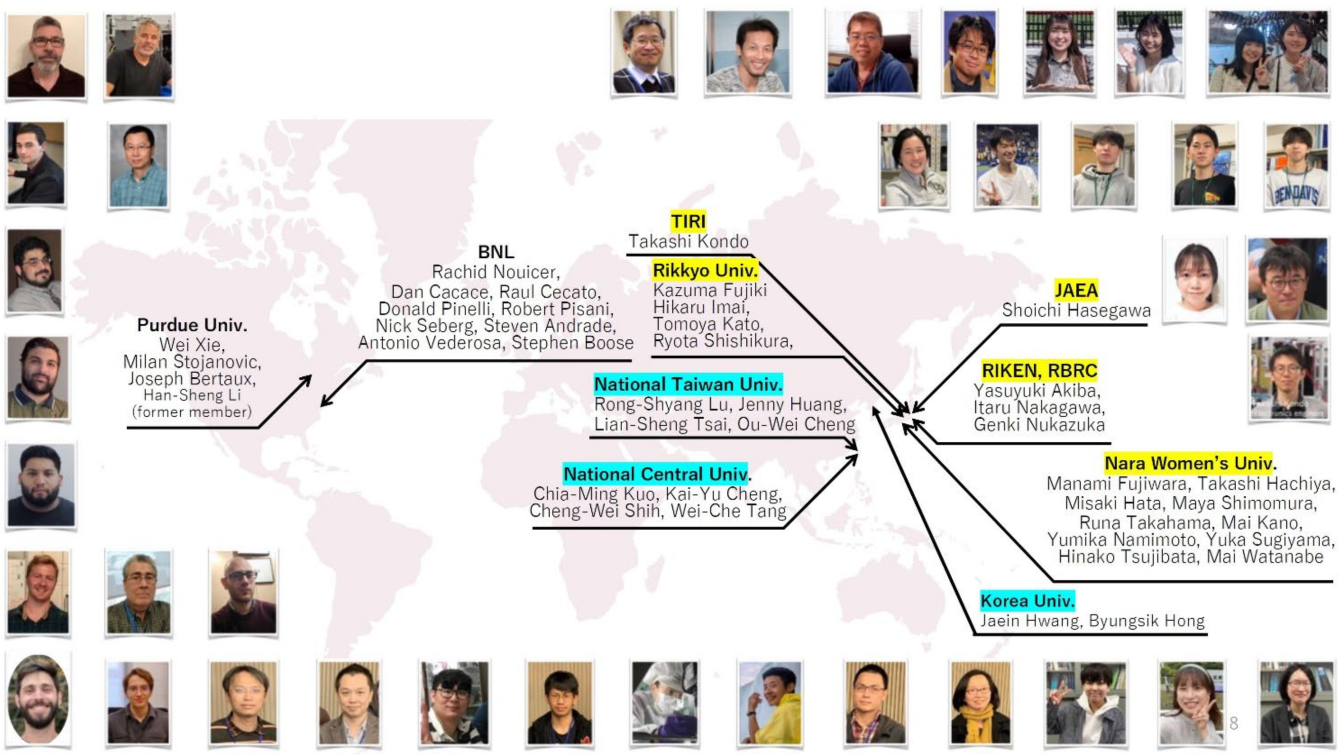

Fig. 2. INTT collaboration.

In the development of INTT, the first step was to make a prototype of one ladder of INTT. The performance of the prototype was then evaluated to confirm that it meets the required performance. If not, improvements were made. After this process was repeated and the ladder prototype meets the required performance, mass production of the ladder started. In this development process process was done by an international collaboration of INTT detector group led by Dr. Nakagawa of this laboratory and Dr. Rachid Nouicer of Brookhaven National Laboratory. The collaboration is shown in Fig. 2.

In the fall of 2022, the construction of the INTT was completed. The detector was in stalled in the sPHENIX in March 2023. The commissioning of the detector started. sPHENIX will start taking data in June 2023.

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List of Publications & Presentations

Publications

[Original Papers]

N. J. Abdulameer *et al*., "Improving constraints oon gluon spin-momentum correlations in transversely polarized protons vias midrapidity open-heavy flavor electrons in $p + p$ collisions at $\sqrt{s} = 200$ GeV," Phys. Rev. D **107**, 052012 (2023).

N. J. Abdulameer *et al*., "Low p_T direct-photon production in Au + Au collisions at $\sqrt{s_{NN}} = 39$ and 62.4 GeV," Phys. Rev. C **107**, 024914 (2023).

N. J. Abdulameer *et al*., "Measurement of second-harmonic Fourier coefficients from azimuthal anisotropies in $p + p$, p + Au, d + Au, and ^{3}He + Au at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **107**, 024907 (2023).

N. J. Abdulameer *et al*., "Measurement of ϕ-meson production in Cu + Au at $\sqrt{s_{NN}} = 200$ GeV and U + U collisions at $\sqrt{s_{NN}} = 193$ GeV," Phys. Rev. C **107**, 014907 (2022).

U. A. Acharya *et al*., "ϕ meson production in p + Al, p + Au, d + Au, ^{3}He + Au collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **106**, 014908 (2022).

U. A. Acharya *et al*., "Measurement of $\psi(2S)$ nuclear modification at backward and forward rapidity in $p+p$, $p+$Al, and $p+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **105**, 064912 (2022).

U. A. Acharya *et al*., "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).

Award

Y. Akiba, "Research of High temperature and high density matter through relativistic heavy ion collisions," Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science, and Technology for 2023.