

Nuclear Science 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 anti-quark polarization with the $W \rightarrow e$ and $W \rightarrow \mu$ measurement. Results 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 $W \rightarrow e$ measurement was published in 2016 and the final results of $W \rightarrow \mu$ 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 to a new experiment and detector, sPHENIX. sPHENIX measures jets, photons, and Upsilon particles to complete the scientific mission of RHIC. We constructed an intermediate-silicon tracker INTT for sPHENIX. The INTT was completed in 2022 and it was installed in sPHENIX in March 2023. The sPHENIX started taking physics data in 2024.

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 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.

(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.

We proposed to upgrade RHICf to RHICf-II. RHICf-II aimed to obtain physics data in 2024 to further elucidate the neutral production cross sections and asymmetries discovered by the RHICf experiment. However, this experiment not approved.

If approved, RHICf-II would 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 was resumed as an associated member and the detector was 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 of the EPIC detector at the EIC.

(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 of RBRC experimental group.

(3) sPHENIX INTT detector

We constructed intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that started operation 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.

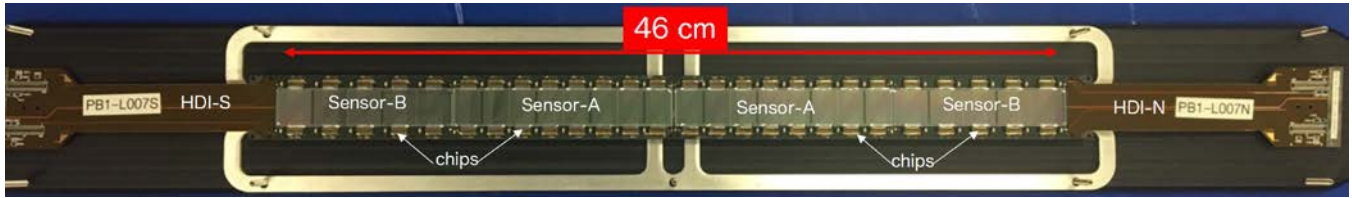


Fig. 1. Left: Completed two halves of INTT detector with members of INTT teams. Right: INTT detector and INTT team just after installation to sPHENIX.

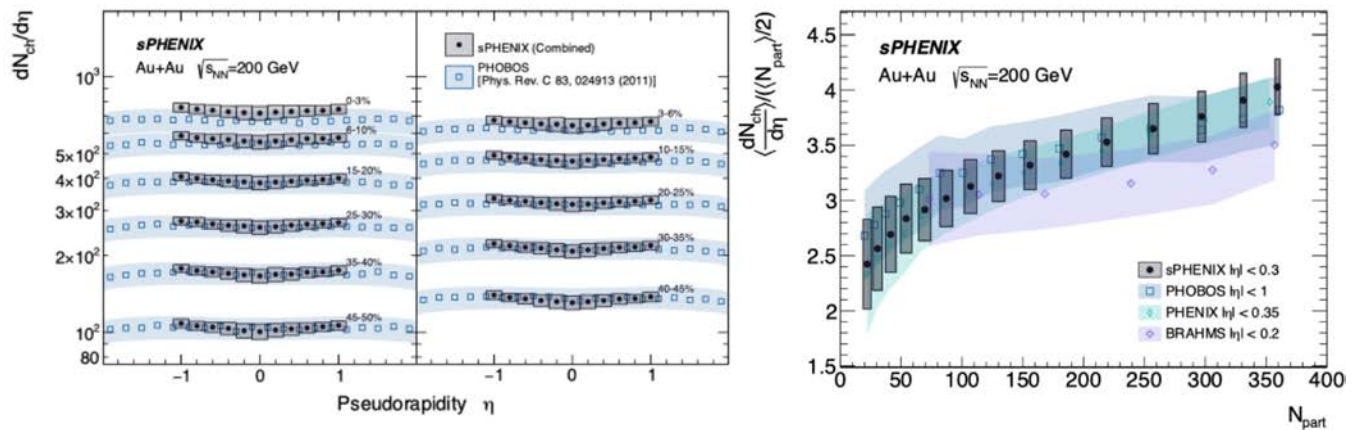
In the development of INTT, the first step was to make a prototype of one ladder of INTT. The performance of the prototype was then evaluated to confirm that it meets the required performance. If not, improvements were made. After this process was repeated and the ladder prototype meets the required 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 installed in the sPHENIX in March 2023. The commissioning of the detector with beam was completed during the 2023 run. The first physics data taking started with polarized $p + p$ beam in the spring of 2024. The INTT detector worked well in the 2024 run. Achievements of the INTT in the 2024 run is presented in the report of RBRC experimental group.

At the end of the 2024 run, RHIC collided Au + Au beams for sPHENIX detector commissioning for Au + Au collisions. In this commissioning run, sPHENIX measured the charged particle multiplicity $dN_{ch}/d\eta$ in Au + Au at $\sqrt{s_{NN}} = 200$ GeV. This is a standard-candle measurement to demonstrate that the entire detector system was working. The results of this measurement is shown in Fig. 3. A paper reporting these results was submitted to publication in Physical Review C. This is one of two first publications of physics results from sPHENIX. The INTT detector is the main detector for this measurement.



Fig. 2. INTT collaboration.

Fig. 3. $dN_{ch}/d\eta$ in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV. Submitted to publication in Physical Review C.

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List of Publications & Presentations**Publications****[Original Papers]**

N. J. Abdulameer *et al.*, “Disentangling centrality bias and final-state effects in the production of high p_T neutral pions using direct photon in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys. Rev. Lett.* **134**, 022302 (2025).

N. J. Abdulameer *et al.*, “Centrality dependence of Levy-stable two-pion Bose-Einstein correlations in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions,” *Phys. Rev. C* **110**, 064909 (2024).

N. J. Abdulameer *et al.*, “Jet modification via π^0 -hadron correlations in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys. Rev. C* **110**, 044901 (2024).

N. J. Abdulameer *et al.*, “Identified charged-hadron production in p + Al, ^3He + Au, and Cu + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in U + U collisions at $\sqrt{s_{NN}} = 193$ GeV,” *Phys. Rev. C* **109**, 054910 (2024).

N. J. Abdulameer *et al.*, “Nonprompt direct-photon production in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys. Rev. C* **109**, 044912 (2024).

N. J. Abdulameer *et al.*, “Charm- and bottom-quark production in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys. Rev. C* **109**, 044907 (2024).

M. H. Kim *et al.*, “Measurement of the transverse single-spin asymmetry for forward neutron production in a wide p_T range in polarized p + p collisions at $\sqrt{s} = 510$ GeV,” *Phys. Rev. D* **109**, 012003 (2024).

Awards

- C. -W. Shih, Poster Presentation Award in “The 12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions.”
- C. -W. Shih, The Association of Asia Pacific Physical Societies (AAPPS) Award