Subnuclear System Research Division
RIKEN BNL Research Center
Experimental Group

1. Abstract

RIKEN BNL Research Center (RBRC) Experimental Group studies the strong interactions (QCD) using 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 at RHIC.

We study the spin structure of the proton using the polarized proton-proton collisions at RHIC. This program has been promoted by RIKEN's leadership. The first focus of the research is to measure the gluon spin contribution to the proton spin. 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 second goal of the spin program is to measure the polarization of anti-quarks in the proton using $W \to e$ and $W \to \mu$ decays. The results of $W \to e$ measurement was published in 2016. 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.

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. We are now studying the property of the QGP. We measured direct photons in Au + Au collisions for $1 < p_{\mathrm{T}} < 3$ GeV/c, where thermal radiation from hot QGP is expected to dominate. The comparison between the data and theory calculations indicates that the initial temperature of 300 MeV to 600 MeV is achieved. These values are well above the transition temperature to QGP, which is calculated to be approximately 160 MeV by lattice QCD calculations.

We had major roles in detector upgrades of PHENIX experiment, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. The VTX is the main device to measure heavy quark (charm and bottom) production and the muon trigger is essential for $W \to \mu$ measurement. The results from the first run with VTX detector in 2011 was published. The results show that electrons from bottom quark decay is strongly suppressed at high p_{T}, but the suppression is weaker than that of charm decay electron for $3 < p_{\mathrm{T}} < 4$ GeV/c. PHENIX recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. A paper on the suppression of electrons from charm and bottom decays in the 2014 run was submitted for publication. The data shows clear different of the suppression of $b \to e$ and $c \to e$.

PHENIX completed its data taking in 2016, and construction of a new detector, sPHENIX, as upgrade of PHENIX was started. 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 (Experimental Group Leader) is the Spokesperson of PHENIX experiment since 2016.

(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 (ALL) 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.

PHENIX measured A_N of single electrons from heavy flavored hadrons at mid rapidity. Production of heavy quarks (charm and bottom) is dominated by gluon-gluon fusion, and the measurement is sensitive to the gluon correlators that are related to the orbital angular momentum of gluons via theoretical models. Figure 1 shows the A_N of single electrons from heavy flavor decays. The data

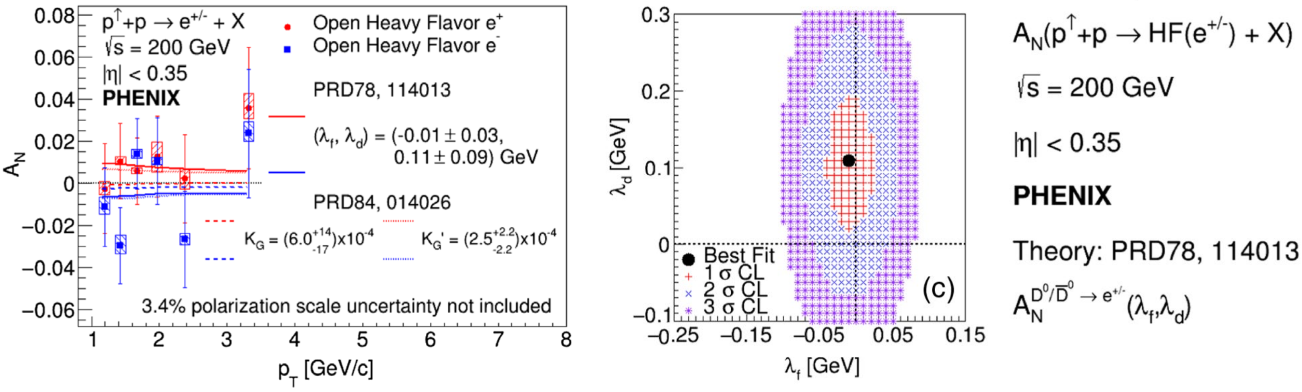

Fig. 1. The single spin asymmetry A_N of heavy flavor decay electrons (left) and the constraint on the model parameter from the data (right). Published in Phys. Rev. D **107**, 052012 (2023).

are compared with a theoretical model by Z. Kang and J. Qiu, and the two parameters λ_f and λ_d of the model are constrained from the data. The right panel of Fig. 1 shows the constraint on the model parameters. The parameters are determined as $\lambda_f = -0.01 \pm 0.03$ GeV and $\lambda_d = 0.11 \pm 0.09$ GeV. The size of these parameters are expected to be O(0.1)GeV. This is the first constraints on these model parameters. These results are published in Physical Review D.

(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. The matter is very dense and opaque, and it has almost no viscosity and behaves like a perfect fluid. These conclusions are primarily based on the following two discoveries:

- Strong suppression of high transverse momentum hadrons in central Au + Au collisions (jet quenching);
- Strong elliptic flow.

These results are summarized in PHENIX White paper, which has more than 3400 citations to date. The focus of the research in heavy ion physics at RHIC is now to investigate the properties of the matter. RBRC have played the leading roles in some of the most important results from PHENIX in the study of the matter properties. These include (1) measurements of heavy quark production from the single electrons from heavy flavor decay (2) measurements of J/ψ production (3) measurements of di-electron continuum and (4) measurements of direct photons.

Our most important result is the measurement of direct photons for $1 < p_{\mathrm{T}} < 5$ GeV/c in $p + p$ and Au + Au through their internal conversion to $e + e^-$ pairs. If the dense partonic matter formed at RHIC is thermalized, it should emit thermal photons. Observation of thermal photon is direct evidence of early thermalization, and we can determine the initial temperature of the matter. It is predicted that thermal photons from QGP phase is the dominant source of direct photons for $1 < p_{\mathrm{T}} < 3$ GeV/c at the RHIC energy. We measured the direct photon in this p_{T} region from measurements of quasi-real virtual photons that decays into low-mass $e + e^-$ pairs. Strong enhancement of direct photon yield in Au + Au over the scaled $p + p$ data has been observed. Several hydrodynamical models can reproduce the central Au + A data within a factor of two. These models assume formation of a hot system with initial temperature of $T_{\mathrm{init}} = 300$ MeV to 600 MeV. This is the first measurement of initial temperature of quark gluon plasma formed at RHIC. Y. Akiba received 2011 Nishina memorial Prize mainly based on this work.

PHENIX experiment recently measured the flow in small collision systems (p + Au, d + Au, and ^{3}He + Au), and observed strong flow in all of these systems. Theoretical models that assume formation of small QGP droplets best describe the data. These results are published in Nature Physics in 2019.

We constructed VTX detector of PHENIX. VTX is a 4-layer silicon tracker and it is the main device for measurement of charm and bottom quark production in PHENIX. VTX took data from the 2011 to 2016 when PHENIX completed data taking. PHENIX recorded high statistics Au + Au data, approximately 20 billion events with VTX in each of the 2014 run and the 2016 run. A paper reporting the results of 2014 run was submitted to Physical Review C.

PHENIX measured the nuclear modification factor of J/ψ and $\psi(2S)$ in the forward and the backward direction in p + Au and d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are shown in Fig. 2.

In the forward rapidity region, the suppression of J/ψ and $\psi(2S)$ is similar. This indicates that initial state effects such as shadowing dominates in this region. In the backward rapidity region, the stronger suppression of $\psi(2S)$ than J/ψ is observed. This result suggests presence of final state effect in p + Au collisions. The paper reporting these results was published in Physical Review C and it was selected as Editor's suggestion.

PHENIX measured low p_{T} direct photons in Au + Au collisions at $\sqrt{s_{NN}} = 39$ and 62 GeV. The yield of these photons exceeds what is expected from $p + p$ collisions at the same energy and it is consistent with large contribution from thermal photons from a hot quark-gluon plasma. Compared with the data of other collision energies, the data suggest that the bulk of thermal photons are

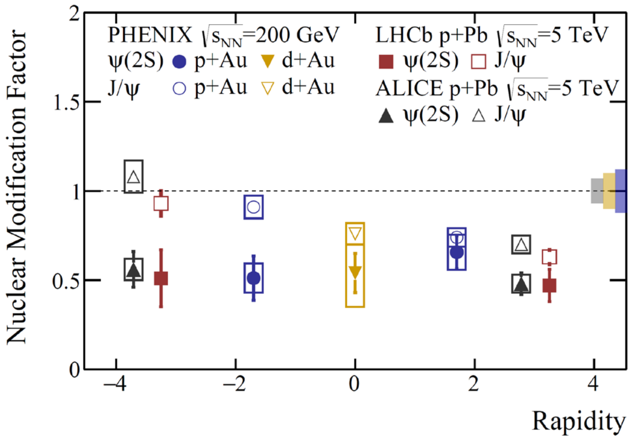

Fig. 2. The nuclear modification factor of J/ψ and $\psi(2S)$ in small collision systems as function of rapidity. Published in Phys. Rev. C **105**, 064912 (2022).

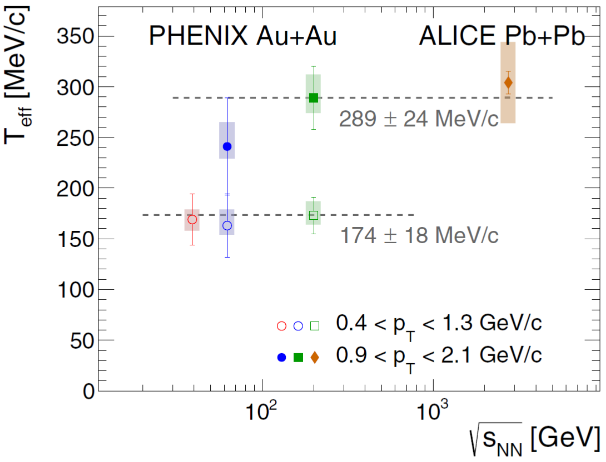

Fig. 3. Effective temperature, T_{eff}, from the low p_{T} direct photon spectra as function of the collision energy. Published in Phys. Rev. C **107**, 024914 (2023).

emitted near the transition of the quark-gluon plasma. The paper reporting these results was published in Physical Review C, and it was selected as Editor's suggestion.

(3) sPHENIX INTT detector

The group had major roles in several PHENIX detector upgrades, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. VTX is a high precision charged particle tracker made of 4 layers of silicon detectors. It is jointly funded by RIKEN and the US DOE. The inner two layers are silicon pixel detectors and the outer two layers are silicon strip detectors. Y. Akiba is the project manager. The VTX detector was completed in November 2010 and subsequently installed in PHENIX. The detector started taking data in the 2011 run. With the new detector, we measure heavy quark (charm and bottom) production in $p + p$, A + A collisions to study the properties of quark-gluon plasma. The final result of the 2011 run was published. The result show that single electrons from bottom quark decay is suppressed, but not as strong as that from charm decay in low p_{T} region ($3 < p_{\mathrm{T}} < 4$ GeV/c). This is the first measurement of suppression of bottom decay electrons at RHIC and the first observation that bottom suppression is smaller than charm. We have recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. The results of bottom/charm ratios in $p + p$ collisions at 200 GeV from the 2015 run was published (Phys. Rev. D **99**, 092003 (2019)). A paper reporting measurements of the nuclear suppression factor R_{AA} of charm and bottom in Au + Au collisions from the 2014 data was submitted for publication to Physical Review C.

PHENIX completed its data taking in 2016. We constructed intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will start taking data in 2023. INTT was completed in fall 2022 and it was installed in sPHENIX in March 2023. sPHENIX will start taking data in June 2023.

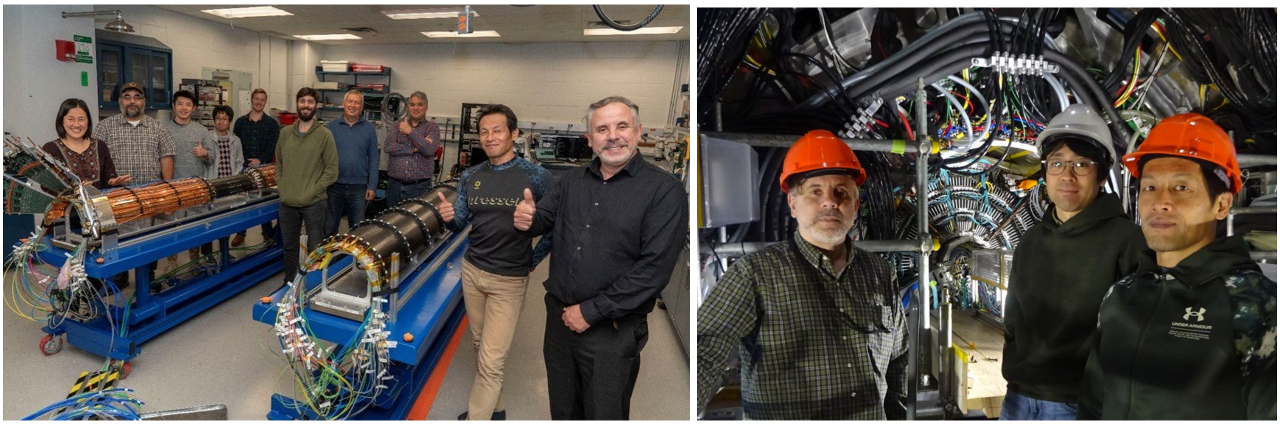

Fig. 4. Left: Completed two halves of INTT detector with members of INTT teams. Right: INTT detector and INTT team just after installation to sPHENIX.

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List of Publications

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 ψ-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.*, “ψ 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.