Final Technical Report

DOE Award: DE-FG02-94ER40821

Strange Particles and Heavy Ion Physics

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April 2016

Abstract

This very long-running grant has supported many experiments in nuclear and particle physics by a group from the University of New Mexico. The gamut of these experiments runs from many aspects of Strangeness Nuclear Physics, to rare Kaon decays, to searches for exotic Hadrons such as Pentaquark or H-Dibaryon, and finally to Spin Physics within the PHENIX collaboration at RHIC. These experiments were performed at a number of laboratories worldwide: first and foremost at Brookhaven National Lab (BNL), but also at CERN, KEK, and most recently at J-PARC. In this Final Technical Report we summarize progress and achievements for this award since our last Progress Report, i.e. for the period of fall 2013 until the award's termination on November 30, 2015.

The report consists of two parts, representing our two most recent experimental efforts, participation in the Nucleon Spin Physics program of the PHENIX experiment at RHIC, the Relativistic Heavy Ion Collider at BNL – Task 1, led by Douglas Fields; and participation in several Strangeness Nuclear Physics experiments at J-PARC, the Japan Proton Accelerator Research Center in Tokai-mura, Japan – Task 2, led by Bernd Bassalleck.

Task 1 – Nucleon Spin Physics at PHENIX (Douglas E. Fields)

2.1.1. Historical Overview

After the group joined the PHENIX effort in 1995, we became involved in both the R&D effort of the muon tracking chambers, as well as the development of the Spin Physics program at RHIC in general. In February 1997, UNM organized a RHIC Spin Physics conference in Española, New Mexico. This conference attracted nearly 25 experimentalist and theorists from around the world to discuss the physics opportunities opening with the new polarized RHIC facility. This meeting lay many of the foundations for the program that is currently reaping results.

In addition to the ongoing effort to build the muon tracking chambers, we led an effort to resolve the problematic issue of how to measure the beam polarization at RHIC. In order to measure a polarization, one needs to measure a production asymmetry (left-right for transversely polarized beams), and know the physics asymmetry, allowing a measurement to determine the polarization as a ratio of those two. Unfortunately, when a new energy regime is being explored, little is known about either. However, theoretical guidance led us to two alternatives: a pion spectrometer and a proton-carbon recoil detector. The first option was rather expensive and had a relatively low figure of merit (combination of statistical significance and asymmetry), but the second option seemed experimentally difficult. From discussions about this problem with RHIC CAD, we became involved in the development of experimental strategies to prove the viability of the proton-carbon recoil polarimeter for RHIC.

Our group then took the lead to develop the silicon based recoil detectors that would be suitable for such an experiment. A test run was proposed at IUCF and successfully carried out. This was followed by a proposal for a run at the Brookhaven AGS and one of our group (Fields) was the co-spokesman for this experiment. This experiment, AGS

E950, measured the asymmetry for polarized proton elastic scattering from a carbon ribbon target at 24GeV/c, measuring the analyzing power which was used as the basis for RHIC polarimetry until the jet polarimeter produced a more accurate data set. In fact, the RHIC polarimeters are basically the same design as was used for E950. In addition to an interesting physics paper and published thesis, this effort has been invaluable to the RHIC spin physics program, without which, there would be no measure of the beam polarization.

Concurrent with this work, the North and South tracking station one chambers were built, installed and commissioned. The South arm was operational in RHIC Run-02, and quickly gave a measurement of the J/Psi meson yield, an important baseline measurement for the QGP studies in heavy-ions. This quick turn-around from data taking to physics results was aided by our group's involvement in the simulation, calibration, and alignment of the South tracking arm. By the start of RHIC Run-03, both muon arms were operational and soon afterwards again yielded physics results. The repair and maintenance of the South arm, installation of the North arm and simultaneous data analysis of the Run-02 data was indeed a herculean feat for all involved.

In fall of 2003, we hired a new postdoctoral associate, Imran Younus, to be stationed for his first two years at BNL. Imran took on the task of working with the maintenance and operation of the muon tracking system. He has basically led that effort, implementing a new FPGA code in the front-end electronics that allowed the muon system to take data at a higher rate, suitable for the upgraded RHIC II luminosity. In addition, Imran played a significant role in keeping the muon tracking system operational throughout the running periods, and fixing problems in the electronics during the summer shutdown periods.

In the fall of 2004, our group developed an idea of how to measure pairs of particles coming from a hard collision at RHIC, and to determine their net transverse momentum. If the partons have a transverse momentum which is correlated to the spin of the proton (orbital angular momentum), then the average transverse momentum of jets which result from the interacting partons should be different for different orientations of the proton's spin. This idea perfectly matched the expertise of one of our postdocs, Jan Rak, and we worked together on this exciting research for several years.

We used this technique to study the early data from our experiment at RHIC. Robert Hobbs wrote his PhD thesis on the RHIC Run 3 data. It was given preliminary status, and although the statistics were very poor, there was some hint of a large effect.

Independently, we worked with Jan in the writing of the paper on jet transverse motion in p+p collisions at RHIC from di-hadron correlations as a member of the paper preparation group (PPG) and the internal review committee (IRC). The paper was published in Physical Review D.

In the spring of 2006, we organized a UNM/RBRC Workshop on Parton Orbital Angular Momentum, Jointly with Gerry Bunce and Werner Vogelsang, to get theorists in the field together with experimentalists to help define the state-of-the-art in the field and get feedback in our research effort. The workshop was very successful, and the proceedings were published by RBRC.

We were approved for preliminary status for our RHIC Run5 data analysis of the k_T asymmetry, and showed our first results in the SPIN06 meeting in Kyoto, Japan. In January, 2010, we finally published our results.

In the meantime, we have continued to develop PHENIX specific hardware projects here at UNM. Beginning in late 2005, our group began an involvement with an upgrade project at PHENIX, the central barrel Silicon Vertex Tracker (VTX), comprised of four silicon layers – two inner pixel layers and two outer strip-pixel layers. The Strip-Pixel sensors were a relatively new and unique design with coiled interleaved strips with charge sharing in two dimensions which allowed for two-dimensional readout with much fewer channels.

Several graduate and undergraduate students in our group put together the facility for testing silicon detectors (re-arranged our existing clean room, built a dark box and electronics for IV and CV measurements, etc.) and performed the prototype testing of the planned Strip-Pixel sensors.

In 2007, we began R&D (in collaboration with LANL and others) on the upgrade forward silicon tracker for PHENIX, the FVTX detector. This complex, $5M project consists of two forward arms, each with four planes of silicon strip detectors covering two-pi in azimuth.

Since we had already been involved with testing of the PHENIX VTX sensors, we took the lead in the R&D for the FVTX sensors, tested the prototype versions, and made recommendations for the production versions to be made by Hammamatsu. We tested (IV and CV curves) each of the production sensors and provided the information in a database to the assembly team.

In addition to the sensor R&D and tests, we took the lead in the design and manufacture of the High-Density Interconnects on which the sensors and the read-out chips would be assembled, and the extension flex cables that connected the wedge assemblies to the Read-Out Cards (ROCs) that processed and shipped the data to the PHENIX counting house. These thin, flex-circuit cards had very critical specifications on trace width, thickness, muti-layering and geometry, and after design, were very challenging to manufacture. In the end, only one vendor was found that had the capability to build them.

With the hiring of Sergey Butsyk as a postdoc (previously at LANL), our group then led the effort in the Front-end Electronic Modules (FEMs) and ROCs. Sergey had already become the collaboration's expert in FPGA programming and debugging, and continued this work through the commissioning and operation of the FVTX in the spring of 2012.

With the successful implementation of the FVTX detector, new physics opportunities have opened up in the PHENIX experiment. The FVTX was primarily designed to differentiate single displaced tracks from tracks originating from the primary interaction point. These displaced tracks are primarily from decays of long-lived resonances such as heavy-flavored mesons, or pions. However, for two-particle (two-muon in the forward arms) decays, the FVTX can be used to distinguish primary decays into two muons (primarily J/Psi and Drell-Yan) from the combinatoric background from hadronic decays. Our graduate student, Aaron Key wrote his thesis on the 2012 and 2013 RHIC runs data on the J/Psi production and double longitudinal spin asymmetry, which will soon result in a nice paper.

Given sufficient statistics then, this may allow us to look at Drell-Yan production *below* the J/Psi mass peak. This kinematic regime is important since recent theoretical evidence suggests that the single-spin asymmetry of Drell-Yan production should be the same as the DIS asymmetry for the same kinematics, but opposite in sign. Confirmation of this QCD result is now an important milestone in this field of physics, and our group hopes to lead this effort at RHIC.

2.1.2. Progress since last report

Aaron Key completed his thesis (J/Psi Double-Longitudinal Asymmetry at Forward Rapidities in 500 GeV p+P Collisions at RHIC) in 2014 while at the same time continuing to develop an FVTX trigger using the available FPGA hardware. This “side project” was used for the first time during RHIC Run 15, and Aaron made himself available to continue to work on this at BNL.

For a semester beginning January 2015, the PI took a sabbatical from UNM in order to be stationed at Brookhaven National Lab during the entire Run 15 and serve as Run Coordinator for the PHENIX experiment. Run 15 included crucial 200 GeV p+p, p+Al and p+Au runs with transverse polarization. In addition to being a major service to the experiment, this allowed him to work with our graduate student, Kathy DeBlasio, stationed there for the data taking period.

Amaresh Datta continued to play the critical role of assistant PHENIX computing coordinator designated as the ‘train conductor’. In this role, he maintained performance and efficiency of the batch-queue system for PHENIX, helped various users on a daily basis and added new file-sets to the batch-queue system as they became available. The ‘conductor’ also coordinates between experts for various detector subsystems and the reconstruction manager. Amaresh also had experience analyzing the vernier scan data from previous runs (needed to determine cross-sections) and helped enable our analysis for Run 15.

During Run-15 data taking, we made a careful measurement of the forward neutron single transverse spin asymmetry in the p+p, p+Au, and p+Al running periods. The 200GeV p+p asymmetry has already been published, but no data has been previously recorded for the asymmetry from heavy-ion collisions with transversely polarized protons. Because of the asymmetric ion species running at RHIC, the DX magnets (the magnets used to focus beams at the collision point) had to be moved, and there was a non-zero angle between the colliding beams and the center-line of the PHENIX experiment. Because of this, special stores had to be arranged with CAD to create a crossing angle which would center the proton beam on the Zero-Degree Calorimeter (ZDC) detector.

We discovered a strong (and unexpected) A-dependence of the single-spin asymmetry. We are involved in the analysis and simulation of this data, and play a strong role in the Paper Preparation Group (PPG) for this work.

Our graduate student, Kathy DeBlasio, and an undergraduate researcher, Gregory Ottino, are just finishing up an analysis of the Run-15 Vernier scan data (p+p) (even though we no longer have the grant to pay them), and Kathy is completing her thesis on the Run-13 J/Psi cross-section.

Gregory Ottino will be continuing to work on PHENIX data as he has taken on the simulation efforts associated with the p-A single-spin asymmetry for his undergraduate honors thesis project, and hopefully a long paper on the x_F and p_T dependence of the neutron asymmetries.

Task 2 – Strangeness Nuclear Physics at J-PARC (Bernd Bassalleck)

Early on this group participated in various experiments in Strangeness Nuclear Physics at the Brookhaven AGS fixed target program, and two K-decay experiments (E865 & E949). The overall focus tended to be on the S=-2 sector, double Hypernuclei and searches for the H-Dibaryon, and also a Strangelet search. Among other contributions, such as leading several data analysis projects, we provided a bank of neutron detectors and associated expertise, and several PhD students graduated with topics from that sector. We also had two successful PhDs from the two above-mentioned AGS (rare) K-decay experiments. After the demise of the AGS fixed target program we shifted our effort to the newly planned and at the time upcoming J-PARC facility in Japan, where Strangeness Nuclear Physics is one of the cornerstones of the physics program. The fact that co-PI Bassalleck ended up serving as Department Chair for ten years (2002 – 2012) limited our J-PARC involvement somewhat.

During the most recent period, i.e. the last couple of years, after stepping down as Chair co-PI Bernd Bassalleck and postdoc Dr. Yuncheng Han continued their involvement in several experiments at J-PARC. Dr. Han was employed by us from September 1, 2013 until December 31, 2014. He was stationed at J-PARC during this entire period, and thus represented our most important contribution to these experimental efforts during the final phase of this award. Until 2015 co-PI Bassalleck typically spent between several weeks and two months per year at J-PARC.

The first real physics production experiment in J-PARC's Hadron Hall was E19, a search for the (much discussed, much searched for, and controversial) Θ^+ pentaquark in the $\pi^- p \rightarrow K^- X$ reaction at beam momenta around 2 GeV/c. Co-PI Bassalleck had been involved in preparations for this experiment since its inception, and participated in its successful initial run in 2010, using the K1.8 beam line and its instrumentation, with results later on published in Phys. Rev. Lett. No signal was observed, and the initial cross section upper limits on the production of this pentaquark were already one order of magnitude lower than the KEK E-522 result, and had demonstrated the capabilities of the new J-PARC facility in its early days.

After the disastrous east Japan earthquake and tsunami in March 2011 more date were taken in spring 2012. Again, no evidence for pentaquark production was observed, and final results were published in 2014 and 2015: M. Moritsu et al., Phys. Rev. C90, 035205 (2014); T.N. Takahashi et al., Proc. of the 2nd International Symposium on Science at J-

PARC, JPS Conf. Proc. 8, 022011 (2015). Below is the abstract of the final Phys. Rev. C paper, summarizing the results:

"The pentaquark Θ^+ has been searched for via the $\pi^- p \rightarrow K^- X$ reaction with beam momenta of 1.92 and 2.01 GeV/c at J-PARC. A missing mass resolution of 2 MeV (FWHM) was achieved but no sharp peak structure was observed. The upper limits on the production cross section averaged over the scattering angle from 2 to 15 degrees in the laboratory frame were found to be less than 0.28 μb/sr at the 90% confidence level for both the 1.92 and 2.01 GeV/c data. The systematic uncertainty of the upper limits was controlled within 10%. Constraints on the Θ^+ decay width were also evaluated with a theoretical calculation using an effective Lagrangian. The present result implies that the width should be less than 0.36 and 1.9 MeV for the spin-parity of 1/2+ and 1/2−, respectively."

After the successful completion of E19 (see above) our focus was on two approved, high-priority experiments in the strangeness S= −2 sector, specifically E07 (A Systematic Study of Ξ^- as well as ΛΛ-Hypernuclei with an Emulsion-Counter Hybrid Method) and E42 (A Search for the Elusive 6-Quark H-Dibaryon with a Large Acceptance Hyperon Spectrometer). E07 is a successor to the successful hybrid emulsion-counter experiment E373 at KEK, searching for ΛΛ-Hypernuclei, see for instance J.K. Ahn et al., Phys. Rev. C88, 014003 (2013). Co-PI Bassalleck had participated in E373 some years ago. E42 builds upon the many previous searches for the fundamental and for decades much-discussed 6-quark H-Dibaryon, this time focusing on high sensitivity in one experiment across the ΛΛ-threshold, from below (where a lightly-bound object could still be hiding) to a possible resonance above threshold (for which there might be some not-statistically-significant hints in earlier KEK experiments). Co-PI Bassalleck has been deeply involved in this physics since the earliest days of double-strangeness investigations at the BNL AGS fixed-target program decades ago. At J-PARC he has remained engaged in these experiments since their inception several years ago. There is very significant overlap between the members of these two collaborations, not surprising, given the physics overlap.

During the final phase of this award postdoc Dr. Han and co-PI Bassalleck worked on several hardware and software projects at J-PARC. For instance, during June 2014 a test run for various detector elements was performed at ELPH (experiment # 2779), the electron accelerator facility at Tohoku University in Sendai, Japan. Both of us were present, setting up, testing, and analyzing the data from a charged-particle hodoscope using MPPCs (multi-pixel photon counters) and wavelength-shifting fiber readout – see S.H. Hwang et al., ELPH Annual Report, Tohoku University, Vol. 2 & 3 (2014).

During 2014 Dr. Han also participated in the emulsion preparation efforts for E07 at Nagoya University. Among his most important contributions were extensive finite element studies of the electric field in the TPC (Time Projection Chamber) being developed for E42. For these studies he used the ELMER finite element software, www.csc.fi/web/elmer. While not physically very large, this TPC nevertheless represents a large-acceptance spectrometer for hyperon decays in E42, as well as other planned experiments. The readout of this TPC is based on GEMs (Gas Electron Multipliers). During his stay at J-PARC in summer of 2014 co-PI Bassalleck participated in bench tests of the initial GEM prototypes that were available at that time. In addition to E-field studies with ELMER, Dr. Han also studied the important E x B effects on the tracks and their impact on overall resolution, using the Garfield++ program. This program was new at the time, and therefore required rather extensive debugging during the set-up phase. He presented his results at the 2nd International Symposium on Science at J-PARC in 2014, see the publications below.

Development of the GEM-TPC for E42, including our contributions is summarized in the following publications: H. Sako et al., Journal of Instrumentation 9, C04009 (2014); H. Sako et al., EPJ Web of Conferences 66, 09015 (2014); Y. Han et al., Proc. 2nd Int. Symp. Science at J-PARC, JPS Conf. Proc. 8, 021002 (2015); S. Hwang et al., Proc. 2nd Int. Symp. Science at J-PARC, JPS Conf. Proc. 8, 022008 (2015).

Since our funding ran out in 2015 we were unfortunately not able to participate in the E07 commissioning run in October 2015. Nevertheless, co-PI Bassalleck has remained involved in progress at J-PARC via Skype meetings and email communications.

Unrelated to any of the above projects is the following recent final publication from BNL E949 (the last rare K-decay experiment at the BNL AGS fixed-target program), in which co-PI Bassalleck and his PhD student Benji Lewis were involved in years ago: Search for heavy neutrinos in $K^+ \rightarrow \mu^+\nu_H$ decays, A.V. Artamonov et al., Phys. Rev. D91, 052001 (2015).