Analyzing Data from Beam Halo at RHIC

Erin Hodson

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Abstract

The QGP phase transition point is beneath 7.7 GeV. RHIC is incapable of colliding two accelerating ions at such low energy levels. Therefore fixed target collisions are studied to learn more about the QGP phase transition point. A fixed target collision simply means that accelerating heavy ions collide with a non-moving target, lowering the momentum exchanged and therefore lowering the energy level of the experiment. A gold plate was installed along the beam pipe at RHIC for the purpose of studying fixed target collisions between the beam halo and the gold plate. However, all previous collisions at RHIC have been between two gold ions. Therefore gold must exist within the beam halo if collisions between the halo and a fixed gold target along the beam pipe are to provide useful data comparable to previous experiments. The main goal of the project was to determine whether gold existed within the halo using Glauber Monte Carlo methods. How the Glauber Model identifies type of ions in collisions will be explained, and data taken from a Single Beam Fixed Target test run at RHIC will be examined. The conclusions reached indicate that heavy ions exist within the halo, and the ongoing task is to use Glauber Monte Carlo methods to determine whether these heavy ions are gold.

1 Background

1.1 Quantum Chromodynamics

In heavy ion physics, heavy ions such as lead or gold are smashed together at high energies for the sake of understanding the strong force. Heavy ions are used for the sake of generating large multiplicities or higher numbers of charged particles. The strong force is to the quarks inside the nuclei as the electroweak force is to electrons and the nucleus. As the electroweak force binds electrons to nuclei, the strong force bind the quarks inside nuclei. This state is known as confinement. During confinement, quarks exist solely within hadrons and not as isolated free particles that can be studied in any laboratory setting. When heavy ions are collided at high energies, however, quarks are freed. This is due to asymptotic freedom, the study of which won the Nobel Prize in 2004 for Drs. Gross, Politzer and Wilczek. Asymptotic freedom states that the coupling constant of the strong force decreases as energy increases. The state of matter in which quarks and gluons act as free particles is known as the Quark Gluon Plasma (QGP). Similar to how water undergoes a phase transition from liquid to vapor, hadronic matter also undergoes a phase transition as quarks are freed from confinement at sufficiently high energies.

1.2 RHIC, STAR, TPC

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab is an accelerator where QGP is being studied through collisions between gold ions. The STAR detector at RHIC is used to gather data. STARs TPC (Time Projection Chamber) is located around the beam pipe and acts as a 70 megapixel digital camera, taking pictures of the tracks left behind by the charged particles created after collisions. Charged particles move through the gas inside the TPC and ionize the gas. The secondary electrons from the ionization process then drift through the TPC. How the charged particles move as a function of time can be documented through images of the particle's tracks. The particles can then be identified based on change in energy due to different types of particles having different masses and therefore losing energy at different rates.

1.3 Beam Halo

As heavy ions are accelerated through the collider, dispersion takes place resulting in what is called the beam halo, which is a less dense region of ions that forms outside the beam. This dispersion can happen as a result of any of the following three processes. First, heavy ions from the beam may collide with beam vacuum gas. Due to the imperfection of the vacuum inside RHIC collisions between ions inside the beam and particles inside the gas can sometimes happen, causing the gold ions of the beam to break apart into lighter ions. Second, a heavy ion might gain an electron from the beam gas. This changes the way the particle accelerates through the magnetic field of the collider, altering its trajectory and resulting in dispersion. Finally, the Coulomb Force contributes to dispersion as a result of all ions in the beam being positively charged. However, details of the composition of the beam halo have not yet been characterized.

2 Project Summary

The Quark Gluon Plasma phase transition point is estimated to exist at an energy lower than 7.7 GeV. RHIC is designed to collide ions at high energies, and as a synchrotron, it makes use of strong magnets in order to do so. As a consequence, RHIC is incapable of sustaining beam in collider mode at low energies. However, since the ions are moving at relativistic speeds energy is proportional to momentum by the Lortentzian four-vector. The collision between a single beam and an unmoving nuclei from a fixed target is therefore lowers the energy of the collision.

A fixed gold target was installed along the beam-pipe in the region 150 200 cm in the z axis. My project was to characterize the collisions taking place in different azimuthal regions of the beam halo using Glauber Model methods to identify types of ions involved. If gold was found then the beam halo could be used in collisions with the fixed gold target, and the QGP transition point could be further studied. In beam-on-beam collisions, the beam halo does not contribute useful data and is considered noise or background. Definitive evidence of gold in the beam halo would allow for an elegant way to study the transition point concurrent with beam-on-beam collision experiments (figure 1).[2]

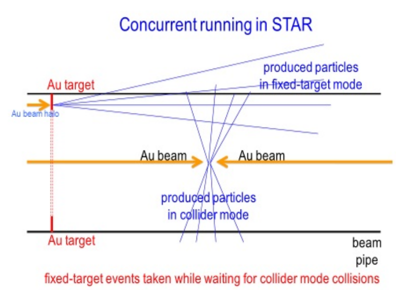

Figure 1: Schemata for Fixed Target Events between beam halo and target occurring simultaneously during beam-on-beam collisions.

2.1 The Experiment

Data was taken from a single beam test run at 9.8 GeV with a s of 4.5 GeV. The use of the single beam was unique for RHIC, which was designed for beam on beam collisions. However, the single beam was pragmatic and used for the sake of simplifying the system. The relevant data needed for the analysis involved collisions between beam halo and beam pipe. Therefore, a double beam experiment could provide no more useful data and would only needlessly complicate the images collected by the TPC by adding more tracks.

In addition, a Fixed Target Trigger was used to minimize lower pion multiplicities (reduce noise) and ensure that only fixed target events were included in the data. A fixed target event is forward facing, and the collider was designed for mid-rapidity studies.[2] The Fixed Target Trigger was designed to collect only such events that deposited energy solely into the East Beam-Beam Counter (BBC), as opposed to events which deposit energy in both East and West BBC as is the case in beam-beam collisions.

3 Methodology

3.1 Glauber Model

Events taking place inside the collider are happening at femtoscopic scales, and so many characteristics of these collisions are unable to be directly measured. The Glauber Model is used to provide estimates regarding the geometric qualities of collisions, such as impact parameter (b), number of participating nucleons (NPart), and the number of binary collisions between nucleons (NColl).

The Glauber Model references the 1950s work of Roy Glauber on quantum mechanical scattering techniques utilized in order to describe the multi-body scattering of composite systems. In the 1970s, Glaubers work was found useful in calculating the total cross section for beams of ions colliding with a target.[4] However, an analytical Glauber Model requires a 2(A+B+1) dimension integral. For two colliding Gold nuclei, this is an integral of over 800 dimensions.[3] However, with the advent of desktop computers another method for creating Glauber Models came to fruition — the Glauber Monte Carlo method. In this method, nucleon positions are drawn randomly from density distributions and projected onto the x-y plane. The colliding nuclei are assigned a random impact parameter, and the NPart and NColl for this event are then calculated by checking whether the distance between any two nucleon centroids fall within the cross section.

The density distributions used in the model are Woods-Saxon distributions.[4] The Woods-Saxon distribution is a charge density function differing from a hard-sphere model of the nuclei by accounting for the fuzzy edge of a nucleis charge-density (figures 2). Rather than forming

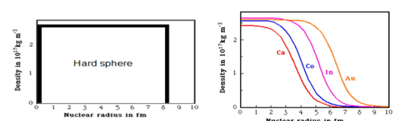

Figure 2: Charge-density distribution of nuclei modeled as a hard sphere (left). Woods-Saxon distributions for different elements (right).

sharp edges and a rectangular distribution, the distribution slopes as characterized by three parameters: nucleis density as measured in the center, the skin depth, and the spherical deviation. The Glauber Model operates by pulling randomly from the distribution for each nucleon in the colliding nuclei. Past quantum scattering experiments provide unique constants for each element, and so the results of the Glauber Model will be dependent upon the types of colliding nuclei being modeled. In this way, the Glauber Model acts as a unique finger print for different types of collisions.

Due to the relatively large phase space in comparison to the femtoscopic nuclei, the colliding nuclei are analogous to darts being thrown at a dartboard. The area of a ring (comparable to cross section) is proportional to the radius (b, the impact parameter) multiplied by the thickness of the ring (db). Similar to how it is more likely for darts thrown randomly to land outside of the targets bulls-eye, the probability of a higher b (or a more peripheral collision) is larger than the probability of a smaller b (corresponding to a head-on collision). Thus for each collision between nuclei being simulated by the Glauber Model, a random b is drawn from the distribution d/db = 2*pi*b.[1]

Given b and the position of each nucleon in each nucleus, the Glauber Model then checks for participating nucleons and binary collisions between nucleons. This is done by checking whether the distance between any pair of nucleons falls within the cross-section. After a set number of trials (100,000 / 1,000,000 / 10,000,000 / etc.) histograms can be filled (figure 3).

3.2 Particle Production Model

The Glauber Model provides estimates drawn from simulations. These simulations become useful due to the monotonic relationship between impact parameter and particle multiplicity. A collision with a smaller impact parameter exchanges more momentum, contains more participating nucleons, and more binary nucleon-nucleon collisions. As a result more charged particles are produced.

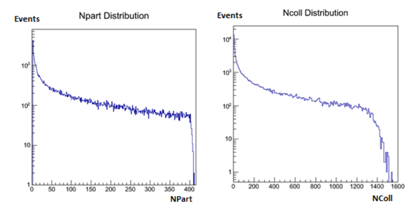

Figure 3: Histogram for NPart (left). NColl distribution referred to as horses back plot (right).

Charged particles can be measured directly by the number of tracks left in the TPC or by the energy deposited in calorimeters. The Particle Production Model refers to plots of the number of charged particles (or total energy from charged particles) as taken from actual data. Previous experiments have found that the number of charged particles produced from various nucleon-nucleon collisions fits to a Negative Binomial Distribution.[5] The parameters of the NBD will vary with the energy level of the experiment, but once found a sample from the NBD can be drawn for each binary nucleon-nucleon collision as estimated by Glauber Model simulations.

The plot for the number of charged particles measured directly during experiment should therefore be comparable to the NColl plot as taken from Glauber Model simulations (figure 4).[1] A comparison between the real data and different Glauber Models for likely collisions (gold-gold, gold-aluminum, aluminum-alpha, etc.) can be made using a simple grid-style Chi Square Fitting.

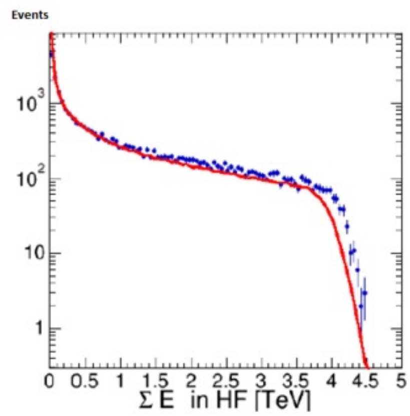

Figure 4: Horses Back plot reproduced from real data in the particle production model.

3.3 Cuts

Cuts along the z axis were made between 150 and 200 cm (figure 5).

The core of the beam was then cut to exclude any events that did not take place between two and five cm, which left only the ions in the halo colliding with the beam pipe. Plotting data after these initial cuts showed two hot spots located on opposite ends of the x axis. Because previous data on the beam halo had shown only one hot spot along the positive x-axis, finding two such regions was unexpected.

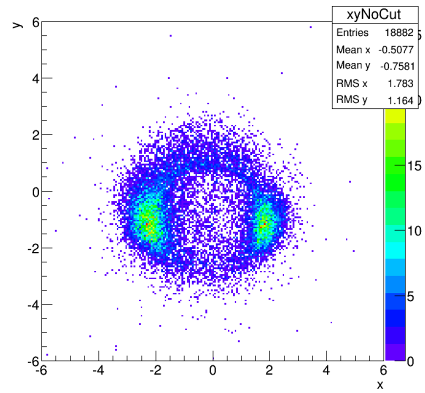

Figure 5

DE/dx (GeV/cm) as a function of momentum and charge was plotted (figure 6, left). At the low energy of the experiment, no antiprotons were produced. Electrons produced were small in number in comparison to the negatively charged pions produced. Therefore, if a particle was negatively charged it was counted as a pion. For positively charged particles, any particle of sigma less than 1 for a proton was excluded. This ensured that a minimum number of protons were counted with the positively charged pions. In addition, any particle of sigma more than two for a pion was excluded. In this way, many of the electrons that had earlier been counted were excluded (figure 6, right).

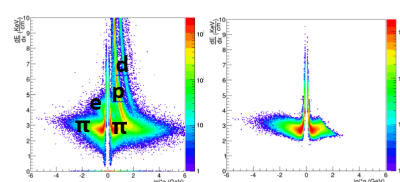

Figure 6: Charged particles prior to cuts (left). Pions left after cuts (right).

The number of pions found after these cuts were made was plotted in comparison to the number of pions found in previous low energy experiments (figure 7). Due to only having only one beam the data from the Single Beam Experiment lacks the smooth gradual drop shown in the plot of the previous 4.5 GeV experiment. Otherwise, the two plots are aligned, which is exactly what one would expect. It can also be noted that the suppression of lower multiplicity events in the Single Beam plot due to the Fixed Target Trigger. In addition, lower multiplicity events were suppressed by the Fixed Target Trigger, which demonstrates that the trigger is functioning properly by minimizing noise due to light elements in the halo colliding.

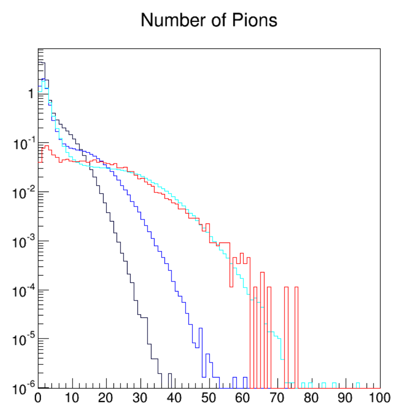

Figure 7: Single Beam Data from experiment at 4.5 GeV shown in red aligns with data taken from previous 4.5 GeV experiments shown in cyan.

The beam halo was split into different regions using additional x and y cuts (figure 8). These cuts were made such that a circle was drawn around the hot spots, and events that fell outside the boundary of this circle were excluded. The positive and negative regions of the y-axis were also demarcated, with the circular regions excluded. This left four distinct regions: positive and negative x regions and positive and negative y regions.

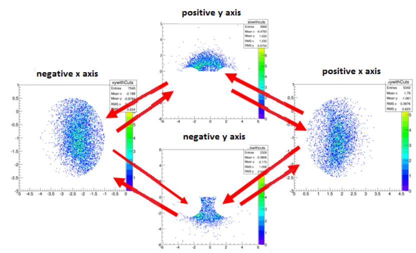

Figure 8: Cuts for different regions of the beam halo with arrows demonstrating how the different sections fit together in the whole.

Each of these four regions was then analyzed, and histograms for the number of pions in each region were filled for comparison.

4 Results

It was initially hypothesized that different regions of the beam halo might contain different ions, for instance that the hot spots contained higher multiplicities indicating that any gold would be more likely to exist in those regions. However, the data showed that although a larger fraction of low multiplicities took place in the positive and negative y regions, all regions of the beam halo contained collisions between similarly heavy ions and the beam pipe (figure 9). This is not unreasonable given the random process of beam collisions with beam-pipe gas, which would result in such an even consistency of the beam halo. That the beam does not change directions in the y axis but only along the x axis, resulting in more collisions, can be stated as a hypothesis to explain the regions along the x axis that contain so many more collisions than the positive and negative y regions. At this stage in the project, the question that remains is whether any of these heavier ions are actually gold or slightly less heavy ions created from collisions with the beam-pipe gas. Glauber Model methods used to demonstrate a match between gold-gold simulations and the data from the single beam test run experiment would provide compelling evidence that the beam halo could be used in fixed target studies in order to learn more about the phase transition point of QGP.

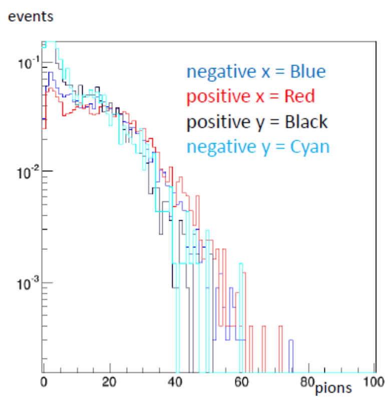

Figure 9: Pions from four different regions from the beam halo.

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