d+Au at PHENIX: Insights on the Cronin Effect, Shadowing and Saturation

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Abstract

Wit Busza pioneered the study of proton-nucleus collisions in order to understand how nucleons lose energy to the nuclear medium and how multiple interactions can affect particle production. These are questions of paramount importance for formation of quark gluon plasma in ion-ion collisions. In this proceedings I report insights on nuclear shadowing, saturation, and the Cronin effect drawn from d+Au collisions at RHIC.

The study of proton-nucleus collisions has been of great interest for many years. Much of the experimental and phenomenological work has been done thanks to the inspiration and leadership of Wit Busza. This remains true at RHIC, where collisions of deuterons on gold nuclei have been used in lieu of p +Au. Beginning in 2015, RHIC will provide proton-nucleus collisions, as well.

In the pre-RHIC era, the big question driving p +A collisions was “What do subsequent p -nucleon collisions in p +A have to do with one another?” Wit Busza was our intellectual leader in addressing this question, and in finding the answer, which was “quite a bit”. Now, the focus has shifted as colliders allow one to probe much smaller values of momentum fraction, x , than was accessible in fixed target experiments. Now, the question is “What do gluons at small x inside a nucleus have to do with one another?” Again, the answer seems to be “quite a bit”, but the range of theoretical predictions, and physics processes which may contribute, is enormous.

Parton distributions in nuclei have been found to differ from those inside

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Rapidity	-1.2 - $\approx$ -2	-0.35 - 0.35	1.2 - $\approx$ 2
direction	backward	mid	forward
region	Au-going anti-shadowing		d-going shadowing

Table 1: Rapidity ranges probed by PHENIX.

nucleons. The fact that the nucleons are bound gives rise to the EMC effect, which is a depletion of partons around $x = 0.7$. Furthermore, nucleons overlap at small x , which should cause the partons to rearrange. Indeed, experiments observe a depletion at small x , < 0.04 (shadowing) and a pile-up, or enhancement, around $x \approx 0.1$ (anti-shadowing). In addition, partons moving inside cold nuclear matter can experience multiple scattering and energy loss. The interplay of this physics is the topic of much discussion and very active research.

To determine how the gluons deep inside a nucleus might interact, PHENIX studies three types of observables. Heavy flavor production is dominantly the result of gluon fusion; PHENIX measures quarkonia and also open heavy flavor via single leptons. Jet pairs result from gluon scattering processes, while direct photons at $p_T > 1 - 2$ GeV/c arise primarily from the QCD Compton scattering process.

1. Heavy Flavor Production

The production of charm + anti-charm or bottom + anti-bottom quark pairs in p+nucleus collisions is dominated by gluon fusion. Consequently, the heavy flavor cross sections in d +Au should be sensitive to the modifications of gluon distributions. Furthermore, their p_T distributions should be sensitive to medium effects upon the incoming or outgoing partons (i.e. before or after the hard scattering producing heavy quarks).

PHENIX measures both open and bound heavy flavor, via semi-leptonic decays and di-leptons, respectively. Single and di-muons are detected at forward and backward rapidities, while electrons, positrons, and e^+e^- pairs are detected at central rapidity. Table 1 shows the rapidity ranges and regions probed in the heavy nucleus.

1.1. Quarkonia

PHENIX was designed to measure the rapidity, p_T , and centrality dependence of J/ψ production, and has successfully carried out these measure-

ments in a number of colliding systems. We observe minimal suppression in peripheral (60-88%) d+Au collisions, but J/ψ is substantially suppressed in the 0-20% most central collisions[1]. Figure 1 shows the nuclear modification factor, which is the ratio of J/ψ yield in d+Au to that in p+p collisions, in peripheral and central collisions[1]. The bottom panel shows the central to peripheral ratio, in which many of the systematic uncertainties cancel. The suppression at forward rapidity is large, exceeding predictions from gluon shadowing as parameterized in EPS09[2] and a J/ψ breakup cross section in the nuclear medium of 4 mb. A larger suppression, very similar to that observed in the data, is expected from gluon saturation, where non-linear gluonic interactions limit, in effect, the gluon density[3, 4]. Both the centrality and the rapidity dependence of the suppression magnitude are closer to saturation expectations.

Figure 1: Nuclear modification factor for J/ψ , as a function of rapidity in peripheral d+Au (top) and central d+Au (middle). The bottom panel shows the ratio.

Of course, increased suppression at forward rapidity is also expected from initial state parton energy loss. Looking differentially in p_T shows further effects of parton scattering in the medium[5]. We observe a p_T broadening that increases with centrality, as expected from initial state multiple scattering. Furthermore, the nuclear modification factor, R_{dA} exceeds 1.0 above 2 GeV/c p_T in backward rapidity; this is the “Cronin effect” which has been interpreted as arising from multiple parton scattering in the Au nucleus prior to the hard scattering which produces the $c + \bar{c}$ pair. J/ψ suppression extends to higher p_T at mid- and forward rapidities, where production is from lower x gluons in the nucleus, and gluon shadowing or saturation becomes important.

It has been a challenge for most models of J/ψ production and breakup to reproduce the triple differential results in rapidity, p_T , and centrality. So, it is remarkable that a recent calculation by Arleo and collaborators successfully reproduces the d+Au data[6]. This work models coherent parton energy loss and p_T broadening from multiple scattering in the nucleus. The energy loss is coherent before and after the hard scattering (i.e. higher twist), yielding a value of the energy loss parameter, $\hat{q}$ of 0.075 GeV²/fm. Though including a saturated gluon distribution in the initial state improves agreement with the data, no J/ψ breakup is included in this calculation. This is somewhat surprising, but the agreement with measured trends suggests that interference between initial and final state radiation by partons passing through nuclei should not be ignored.

Figure 2: Nuclear modification factor for ψ' , compared to J/ψ , as a function of centrality in d+Au (left). Ratio of ψ' to J/ψ , as a function of associated charged particle multiplicity (right).

Breakup effects can be tested by comparing J/ψ with smaller, more tightly bound probes (e.g. Υ) and larger, loosely bound probes, such as ψ' . PHENIX finds the Υ yield in d+Au to be consistent with expectations from EPS09 and some nuclear breakup, but the statistical uncertainties are too large to provide a strong constraint[7]. Mid-rapidity ψ' , on the other hand, provide clear evidence of final state breakup[8]. As is visible from the left panel of Figure 2, ψ' production is suppressed more than J/ψ in d+Au. This cannot be due to shadowing or initial state parton energy loss, as these processes would affect the $c + \bar{c}$ precursor to the bound states. The right panel shows that the ratio of ψ' to J/ψ yields decreases linearly with the charged particle multiplicity. This is exactly as would be expected from final state breakup of the bound quarkonia, as the ψ' is less tightly bound than the J/ψ , and is thus easier to dissociate. The ψ' breakup measured by PHENIX is larger than that observed in lower energy p+A collisions (800 GeV protons on fixed targets), even though the time spent in the nucleus is very short at RHIC. This suggests late stage breakup of the quarkonia, as for example, would be caused by co-moving hadrons. This hypothesis will be checked by PHENIX, using the new forward silicon FVTX detector to separate ψ' from J/ψ at forward rapidity. Changing the rapidity allows us to tune the number of co-moving hadrons.

1.2. Open Heavy Flavor

PHENIX measures open heavy flavor via semi-leptonic decays. Single electrons from D and B mesons are measured at mid-rapidity and single muons at forward and backward rapidity. Continuum intermediate mass lepton pairs provide information on $c + \bar{c}$ and $b + \bar{b}$ pairs.

The rapidity dependence of single leptons shows clear enhancement in the backward (Au-going) direction, increasing with d+Au collision centrality[9]. Backward rapidity is sensitive to large x in the Au nucleus; heavy flavor production can be enhanced in the anti-shadowing regime where the gluon density in nuclei is higher than in protons. Conversely, in the forward (d-going) direction, there is a suppression of open heavy flavor, as expected from gluon shadowing or saturation. Remarkably, enhancement is also observed in central collisions at mid-rapidity[10]. The enhancement occurs at $p_T < 5$ GeV/c, and can be expected from parton multiple scattering, similarly to the observed J/ψ p_T broadening. This is the “classic” explanation for the Cronin effect. However, it should be noted that the proton yield is more

enhanced in central d+Au than pion and kaon yields[11], which is not consistent with parton initial state multiple scattering alone. After all, a parton making its way through a nucleus, and experiencing multiple scattering along its path, has no knowledge of how it will ultimately fragment. Perhaps coherence between initial and final state parton scattering and energy loss can resolve the conundrum?

Figure 3: The nuclear modification factors, averaged over $1 < p_T < 3 \text{ GeV}/c$ (a) and $3 < p_T < 5 \text{ GeV}/c$ (b), for heavy flavor electrons at midrapidity in d+Au, Cu+Cu, and Au+Au collisions plotted as a function of N_{coll} .

Of course, if open heavy flavor production is enhanced in the nuclear medium, the baseline for the previously observed *suppression* in Au+Au is different from that given by p+p collisions. To better quantify this, PHENIX performed a systematic study of non-photonic single electrons at mid-rapidity in p+p, p+Au, Cu+Cu, and Au+Au collisions[12]. With such a broad range of colliding systems it is possible to select centrality bins to compare d+A and A+A with a similar number of binary nucleon-nucleon collisions. With such selections, the open heavy flavor enhancement is identical in Cu+Cu and d+Au. This can be seen in Figure 3, which shows the mean R_{AA} for $1 < p_T < 3$ and $3 < p_T < 5$, for three colliding systems, as a function of N_{coll} . It is clear that all three systems (with the exception of the first Au+Au point) follow a common dependence on N_{coll} . This dependence indicates enhanced open heavy flavor production in cold nuclear matter, followed by suppression by quark gluon plasma in A+A collisions. The cold nuclear matter enhancement may explain the difference in the R_{AA} values observed for non-photonic electrons and pions in central Au+Au collisions.

1.3. Intermediate Mass di-electrons

The intermediate mass region in the e^+e^- mass spectrum, between the ϕ and J/ψ , is dominated by semi-leptonic decays of heavy quark anti-quark pairs. PHENIX measured the di-electron spectrum in d+Au with high statistics, and performed a double differential analysis in mass and p_T [13]. At low p_T , charm dominates the mass region between 1 and 3 GeV/ c^2 , however bottom decays dominate for $p_T > 2.5$ GeV/ c . This offers a way to separate charm and bottom without reconstructing decay vertices.

We utilize PYTHIA and MC@NLO predictions of the shape of the double differential spectra, requiring that the e^+ and e^- fall inside the PHENIX central arm acceptance. The shape of the double differential spectra is calculated from the event generators, and the normalization is fitted to the data to determine the charm and bottom cross sections. The shapes of the spectra appear fairly similar, however, the two simulations predict very different correlations between the q and $\bar{q}$. In PYTHIA the correlation is driven by the particular implementation of intrinsic k_T , while in MC@NLO it arises from next to leading order terms in the calculation. Remarkably, rather different total cross sections produce the same di-electron distributions at central rapidity.

For bottom decays, the fraction of di-electrons at midrapidity, and therefore also in the PHENIX acceptance, is primarily determined by the decay kinematics of the two independent semi-leptonic decays and is not sensitive to the substantial model dependence of the $b - \bar{b}$ correlations. For the same reason, the fraction of di-electrons at midrapidity should not be sensitive to possible modifications of the momenta for b and $\bar{b}$ due to cold nuclear matter effects. Determination of the $b + \bar{b}$ cross section thus has little model dependence and the measured di-electron double differential spectra can be used to reliably calculate the production cross section. The result is

$$\sigma_{b\bar{b}}^{dAu} = 1.37 \pm 0.28(stat) \pm 0.46(syst) \text{ mb}, \quad (1)$$

The determination of the charm cross section is less reliable due to the lower mass of the charm quark. This causes the opening angle between the electron and positron to reflect the $c - \bar{c}$ correlation, even though the correlations is somewhat smeared by the decay kinematics. Consequently, there is a model dependence in the di-electron spectra arising from differences in the $c - \bar{c}$ correlations in LO and NLO calculations; the additional gluon emission in MC@NLO causes a deviation from back-to-back $c - \bar{c}$ opening

angle. Indeed, PYTHIA fitted to the data results in $\sigma_{cc}^{pp} = 385 \pm 34(stat) \pm 119(syst) \mu b$ while MC@NLO yields $\sigma_{cc}^{pp} = 958 \pm 96(stat) \pm 335(syst) \mu b$. This large model dependence does not allow accurate determination of the charm cross section from a di-electron measurement. It should be noted that the model dependence of the pair acceptance is already substantial for detection of pairs with mass $> 1.16 \text{ GeV}/c^2$ in one unit of rapidity, even for full azimuthal acceptance.

A direct search for cold nuclear matter effects will be possible by comparing the double differential spectra in d+Au with those in p+p collisions. The current result should already help to constrain models of cold nuclear matter effects on heavy quark production.

2. Direct Photon Production

PHENIX has measured direct photons in d+Au collisions at mid-rapidity using two techniques. The electromagnetic calorimeters detect inclusive photons, which include photons from decays as well as direct photons. Reconstructing neutral mesons from photon pairs allows precise measurement of their spectra, which are then subtracted from the inclusive photon spectrum. For p_T below 5 GeV/c, direct photons are measured using the virtual photon technique[14]. In this method, the virtual photon spectrum is measured via low mass di-electrons which have a p_T substantially larger than their mass. By extrapolating the mass dependent yield down to zero mass, one can determine the real photon spectrum. This technique is effective as low as $p_T = 1 \text{ GeV}/c$.

Putting together the two methods to measure direct photon spectra in p+p and d+Au allows determination of R_{dA} from $1 < p_T < 18 \text{ GeV}/c$. The results can be compared to calculations including various combinations of the Cronin effect, the isospin dependence of photon production, nuclear shadowing, and initial state energy loss. The data are consistent with a slight enhancement of R_{dA} below 5 GeV/c from the Cronin effect[15]. However, no statistically significant nuclear modification is observed beyond this. The data have limited sensitivity at higher p_T , where isospin and energy loss effects are manifested. It may not be surprising that no shadowing effects are observed, as the x probed at mid-rapidity is just between the shadowing and anti-shadowing regimes. Accessing the shadowing regime requires measuring direct photons at forward rapidity ($y \geq 2$).

Figure 4: Ratio of the hadron-pair rate in peripheral and central d+Au to p+p. For $x_{frag} > 10^{-3}$, some data points have been offset from their true x_{frag} to avoid overlap. The central point in the groups of three are at the correct x_{frag} .

Di-hadron correlations do show first hints for gluon saturation[16], as can be seen in Figure 4. This figure shows the ratio of hadron pairs from di-jets in d+Au to that in p+p collisions (the ratio is labeled J_{dA}), plotted as a function of the approximate value of x in the Au nucleus. The x estimate is made using $x_{Au}^{frag} = (\langle p_{T1} \rangle e^{-(\eta_1)} + \langle p_{T2} \rangle e^{-(\eta_2)}) / \sqrt{s_{NN}}$ for all pairs in η and p_T . Peripheral d+Au collisions have J_{dA} consistent with 1 for all values of x . Central d+Au collisions, on the other hand, show a strong decrease with decreasing x . For hadron pairs where both are detected at forward rapidity, the suppression is striking. Exactly such behavior is expected if the p_T of an outgoing parton is balanced by many gluons behaving as a classical field, i.e. hard scattering off a saturated gluon field. The modest p_T of the hadrons used in this analysis complicate the interpretation of these data, unfortunately, due to non-perturbative effects. However, the first hints are intriguing, and are also seen in a preliminary result from the STAR Collaboration.

Initial state shadowing or saturation can be better quantified using direct photons from QCD Compton scattering at forward rapidity. PHENIX will measure direct photons at both forward and backward rapidities in the 2015 RHIC run using the new MPC-EX detector[17]. This upgrade consists of a pair of new Si/W preshower detectors placed in front of the existing lead tungstate crystals in the muon piston calorimeter (MPC). Each preshower detector consists of 8 alternating layers of tungsten absorber and silicon pixel detectors. The pixels are arranged to provide 4 layers with high precision

in each of the two transverse directions. The preshower detector will allow PHENIX to reconstruct π^0 and η mesons, and therefore to determine the yield and distribution of prompt photons out to momenta of 80 GeV/c. The detector was recently tested at SLAC, using beams of single electrons and somewhat separated electron pairs. The test beam data will allow careful tuning of the reconstruction algorithms. This measurement will substantially improve our knowledge of the nuclear parton distribution functions down to $x \approx 10^{-3}$ in the next run.

3. Beyond p+A

It is important to note that in proton-nucleus collisions we probe cold nuclear matter with a parton, not a photon or lepton, and consequently strong interactions with the cold matter can affect our probe. Partons passing through matter can lose energy before and/or after the hard scattering. Partons can also experience multiple soft scatterings. Furthermore, all of these processes may not be independent of one another! Indeed, J/ψ , open heavy flavor and moderate p_T hadron data from d+Au all show some evidence for coherent effects on partonic probes. While these effects can be considered as “background” for measurement of the nuclear PDF’s, the physics of coherent parton interactions with nuclei is very interesting in its own right. Furthermore, parton interactions in cold nuclear matter are directly relevant to understanding how partons interact with quark gluon plasma.

So, what to do? It will be important to make measurements that allow us to pick these effects apart, as well as to turn them off entirely. In the short term, we should (and will!) measure not only the direct photon spectra, but also direct photon-hadron or direct photon-jet correlations in p+A collisions. The direct photon will reflect initial state effects on the partonic probe, but of course the photon has no strong interactions in the final state. Correlations of hadrons from the opposing parton with the direct photon should be affected by final state scattering and/or energy loss of the scattered parton as well as any initial state scattering of the incoming partons. Consequently, it will be very informative to compare γ_{direct} - h correlations in p+A and p+p collisions to get a handle on the final state scattering and energy loss. With the MPC-EX and the central arm spectrometers, PHENIX will be able to do these measurements as a function of x in the Au nucleus and also measure the opening angle between the photon and hadron. This is a very exciting

opportunity, as it will allow determination of the final state effects as a function of the gluon density in the nucleus.

Pinning down the initial state effects will be more difficult. Ideally, one would like to use an electromagnetic, rather than strongly interacting, probe to turn them off. A first peek at the gluon structure of the nucleus can be had using coherent photoproduction of vector mesons in ultra-peripheral nucleus-nucleus collisions. In this case, there are no initial state effects on the probe. ALICE has made a measurement of the rapidity dependence of J/ψ in ultra-peripheral Pb+Pb collisions [18, 19, 20]. The yield at mid-rapidity provides discriminating power among different models of the gluon distribution in the Pb nucleus. However, the statistics at this time are primarily concentrated at low p_T , where non-perturbative effects are important because the scattering is only approximately “hard”. While various authors have calculated these non-perturbative effects, their presence clouds interpretation of the data.

A cleaner way to probe the gluon distribution deep inside nuclei is to use an electron as the probe. In order to reach low x with sufficient Q^2 to avoid strong non-perturbative effects, an electron-ion collider is needed. Using the heaviest possible nuclei allows probing the physics of a possibly saturated gluon distribution at Q^2 around 1 GeV². Design work is underway at both Brookhaven and Jefferson Lab in the U.S. Furthermore, a concept for a LHeC is being developed at CERN. At Brookhaven, an electron linac would be added to RHIC to form e-RHIC, while at Jefferson Lab, a hadron accelerator would be added to CEBAF for MEIC/EIC. $\sqrt{s}$ from 45 to 90 GeV is envisioned at e-RHIC, and somewhat lower $\sqrt{s}$ at MEIC/EIC.

Combining these results with the insights from p-A collisions in the near term should allow us to quantify initial and final state scattering and energy loss of partonic probes. With help from the theory community we will hopefully be able to determine how coherent these effects might be. Of course, should this physics be found to be important (as this author suspects), we will need to rethink the methodology for extracting nuclear PDF’s from data. The current strategy of fitting e+A and p/d+A data simultaneously may prove not to be the ideal approach.

So, remarkably enough, even though we are now probing the partonic world rather than dealing with nucleons, we are once again pondering the questions pioneered by Wit Busza. How do partons lose energy to the nuclear medium? How do multiple interactions affect particle production? It will certainly be exciting to find out!

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