BeAGLE: A Tool to Refine Detector Requirements for eA Collisions
EIC R&D Project eRD17: Progress Report (January-June 2018) and Proposal

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Abstract

The BeAGLE program for simulating e+A collisions, largely developed as an EIC R&D project (eRD17), is beginning to be used to investigate the detector requirements, particularly in the forward region (ion-going direction) for both eRHIC and JLEIC. As discussed in previous reports, tagging of incoherent diffractive e+A collisions (where the nucleus is excited diffractively and emits particles) is an important physics topic which is likely to be very demanding on the forward detector and the forward detector/IR integration. We have made progress on and propose to continue the effort we proposed one year ago: extending BeAGLE to better describe diffractive physics in e+A collisions. This will allow us to tune to the relevant E665 event-by-event e+A streamer chamber data and validate BeAGLE's physics model (DIS+diffraction+nuclear effects). Such validation is essential in order to understand how well the detector/IR designs support this physics already and to understand detector requirements and physics tradeoffs in detector/IR design decisions.

Coherent diffraction, where the nucleus stays intact without emitting particles, with a cross-section proportional to the *square* of the gluon distribution, plays a key role in EIC e+A physics and the study of parton saturation. It is a demanding measurement since the incoherent cross-section is expected to be 100–430 times as large as the coherent cross-section in the second and third "dips" of the coherent cross-section, exactly where you most need precision. As discussed previously, as many as 12% of the incoherent events emit *no* evaporation neutrons, leaving a S/N ratio in the range 1/36–1/12 rather than the desired 1:1 or 3:1 if you rely on them

alone. We have made some progress on understanding the ability of the ZDC to measure knockout neutrons and de-excitation photons, using the existing BeAGLE framework. These results are encouraging, but indicate that knockout protons will also need to be detected. Because the result has such a strong implication for forward detector / IR design, it is imperative to validate the model with more — and more relevant — data.

We therefore propose, during the remainder of FY2018 along with FY2019, to finish implementing BeAGLE w/ RAPGAP and to focus on tuning to the most relevant data to ensure that the conclusions are valid. In particular, our goal is to answer the question: Is it true that the intranuclear cascade (INC) effects are so modest in inelastic eA events (DIS & incoherent diffraction)? Practically this means confirming using event-by-event full acceptance μ+Xe data at a relevant s (E665 Streamer Chamber) that the INC formation time parameter τ_0 is in the range 5–7 fm/c as opposed to the naive expectation of 1–2 fm/c. This will allow us to best understand the detector requirements for the critical and demanding physics measurement: coherent diffraction in e+A collisions.

1 Introduction

As mentioned in the abstract and detailed below, a better simulation of diffraction in e+A collisions is *essential* to EIC physics and to determining the detector requirements. In particular, vetoing diffractive e+A events where the nucleus does not stay intact is challenging and we need a more accurate simulation than that provided by Pythia [1], combining the improved description of $\gamma^* N$ diffraction from RAPGAP [2] with the DPMJET-based [3] description of the formation-time intranuclear cascade, nuclear evaporation and breakup built into BeAGLE [4]. This will allow us to validate the model, fitting HERA e+p forward proton [5] and neutron data [6] along with E665 average evaporation neutron data [7] and event-by-event streamer chamber data [8].

The organization of the remainder of the document is as follows. Section 2 summarizes the progress of the project from January-June 2018, as well as answering a question from the committee from the January 2018 meeting. Section 3 outlines the plans for the summer. Section 4 contains the proposal for the second year of our FY2018-2019 effort: upgrading BeAGLE to include a better description of diffraction by adding RAPGAP and confronting BeAGLE with a more complete set of E665 data. This would lead to a version of BeAGLE which will be optimal for understanding the tradeoffs between the completeness and quality of forward detection on the one hand and our ability to measure transverse spatial nuclear gluon distributions and saturation on the other. Section 5 discusses external funding as well as other projects and proposals involving BeAGLE and their synergy with eRD17. Finally, Section 6 contains a summary of the progress report and proposal.

1.1 EIC Physics Motivation for the Project

The EIC White Paper [9] states the importance of diffraction as well as the experimental challenges quite clearly: "What makes the diffractive processes so interesting is that they are most sensitive to the underlying gluon distribution, and that they are the *only* known class of events that allows us to gain insight into the spatial distribution of gluons in nuclei. However, while the physics goals are golden, the technical challenges are formidable but not insurmountable, and require careful planning of the detector and interaction region." [Emphasis in the original].

Exclusive coherent vector meson production $e + A \rightarrow e' + V + A$ where the nucleus remains intact is expected to be one of the most important measurements at the EIC [9]. The measured quantity $d\sigma/dt$ can be directly related, through a Fourier-like transform, to the transverse spatial distribution of gluons in the nucleus $F(b)$. For Bjorken-x values $x < 0.01$ and at modest values of Q^2 (say $Q^2 > 1$ GeV^2), the effective renormalization scale, μ^2, at which we are sampling the gluon distribution $G(x, \mu^2)$ is $\mu^2 \sim \max(Q^2, M_V^2)$. The J/ψ particle, with $M^2 = 9.6$ GeV^2 should effectively sample the baseline, unsaturated, gluon distribution, while the ϕ particle with $M^2 = 1.0$ GeV^2 should be directly sensitive to gluon saturation as a function of Q^2.

Exclusive *incoherent* vector meson production in nuclei $e+A \rightarrow e'+V+X$ occurs when the nucleus breaks up due to its interaction with the vector meson. This physics is quite interesting in its own right and so it will be important to identify these events. The really challenging issue, though, is that for high values of $|t|$, the incoherent production swamps the coherent production and we need to be able to veto the incoherent case in order to measure the coherent production.

Studies using Sar*t*re [10, 11] indicate that in order to measure the gluon spatial distribution precisely with coherent production, you need to include the third dip in the spectrum, going out to $|t| \sim 0.15$ GeV^2, although you get a reasonable measurement with just the first two dips. If you omit the second dip, you make errors comparable to the expected size of the saturation effect. This allows us to set the scale for the required background rejection. Figure 1 shows the expected results for the J/ψ in the presence of saturation and in a model without saturation. Saturation actually makes our job easier by suppressing the background, but only slightly in the case of the J/ψ. The minimum requirement for any reasonable measurement would be that we need to be able to achieve a 1:1 S/N ratio for the second dip of the J/ψ which requires a one-hundred fold reduction in background or a 99% veto-tagging efficiency. A much better goal would be to achieve a 3:1 S/N ratio for the third dip which requires a 1300-fold reduction in background or a 99.92% veto efficiency. So our target veto efficiency should be 99–99.92%.

The white paper was written before BeAGLE was available and its predecessor, DPM-JetHybrid [12], was itself rather new. Therefore the quick studies of the detector capabilities used some crude estimates of how the nucleus would respond to an exclusive incoherent diffractive event. In particular, the nuclear excitation energy was assumed to be, on average, more than 10x larger than BeAGLE indicates it should be. Based on those crude assumptions, the white paper concluded that: "the nuclear breakup in incoherent diffrac-

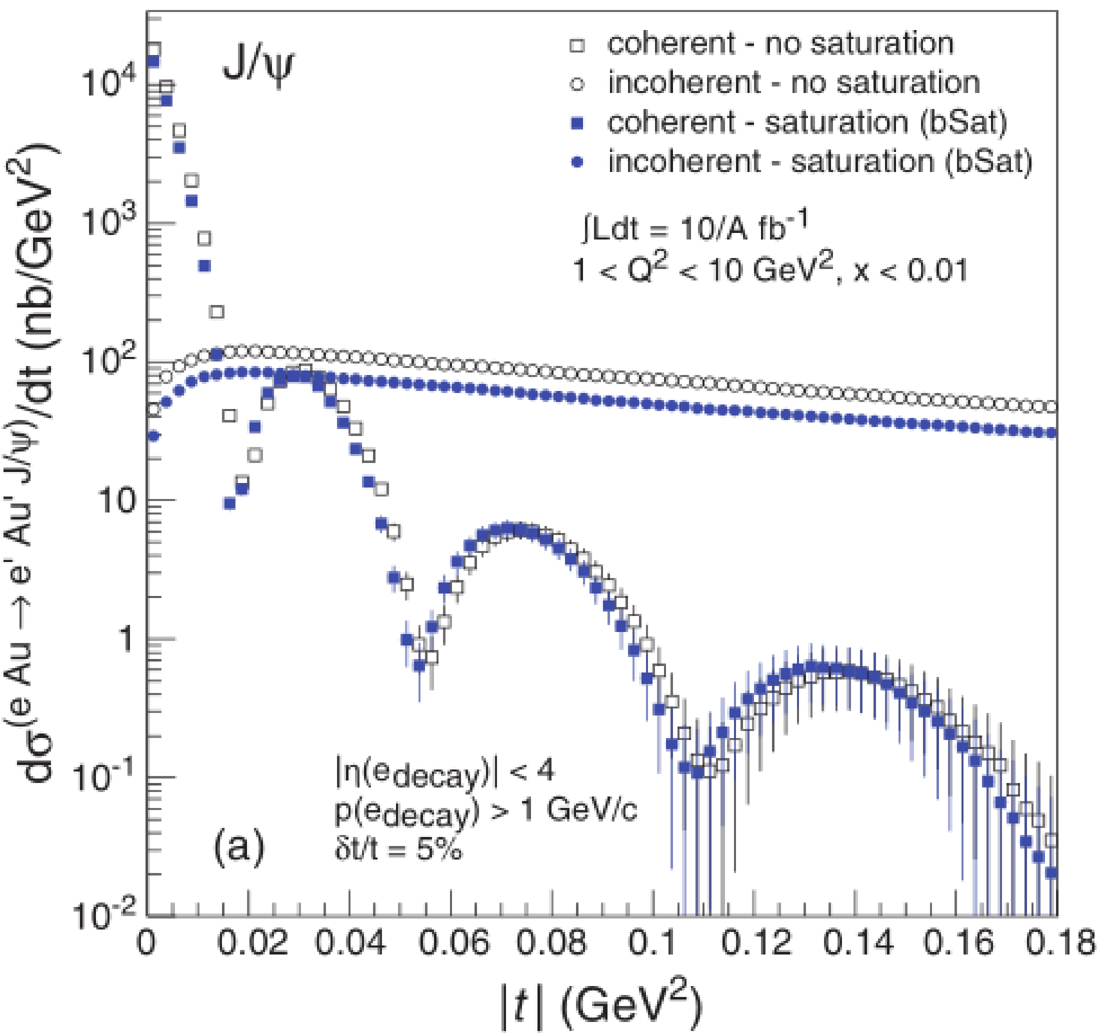


Figure 1: Cross-section for exclusive, coherent and incoherent, J/ψ production with and without saturation from Sar*t*re [9, 11].

tion can be detected with close to 100% efficiency by measuring the emitted neutrons in a zero degree calorimeter placed after the first dipole magnet that bends the hadron beam."

The current incarnation of BeAGLE has two features in the description of diffraction which need improvement. It uses Pythia rather than RAPGAP to estimate the behavior of diffractive events, and it also assumes that diffractive and DIS events have effectively the same dipole cross-section. Nevertheless, because it includes a good simulation of the multinucleon interaction, intranuclear cascade and nuclear evaporation and breakup, it is currently our best tool to estimate our vetoing efficiency. As discussed in last year's proposal [13], BeAGLE indicates the surprising result that even at high values of $|t|$, there are *zero* evaporation neutrons in more than 12% of the events! Basically, there is a chance that the struck nucleon is knocked cleanly out of the nucleus and the remnant nucleus manages to de-excite without neutron evaporation. The current BeAGLE estimate veto-tagging efficiency based on evaporation neutrons alone is about 88%, far short of the target 99–99.92%. The S/N at the second dip would be about 1:12 and at the third dip 1:36.

Of course, there are likely other particles in the event which will increase our ability to tag these events, but the main point is that the challenge is even greater than assumed in the white paper, and this study needs to be done. In summary:

1. The incoherent diffractive events described by BeAGLE are one of the most sensitive probes of saturation [9], and we need to make sure that we can identify them and measure their properties, ideally including geometry tagging (impact parameter).

2. In order to demonstrate our ability to achieve background rejection factors of 100–1300, we need an accurate description of the physics, and presumably a very good detector. This may be one of the key design drivers for forward detection and the IRs.

3. Until EIC comes online, the old E665 data provides our best chance to tune our models and understand what we can expect.

For eRD17, due to the importance of diffractive physics, including both incoherent and coherent, we proposed a two year project for FY2018–2019 to improve BeAGLE's description of diffraction in several ways. First, we will implement a process-dependent effective "dipole" cross-section in BeAGLE. This will modify the relative A-dependence between diffraction and DIS (and possibly higher order hard processes). It will also allow the nucleus to respond differently to diffractive and DIS events. Second, we will implement RAPGAP as an alternative model to PYTHIA, controllable by a switch within BeAGLE. RAPGAP uses PYTHIA for fragmentation, but has a more sophisticated and up-to-date description of e+p diffraction physics. Finally, we will engage in a more comprehensive effort to confront BeAGLE with all relevant data. The E665 forward neutron data for e+Pb and e+Ca [7] and especially the E665 Streamer Chamber data [8] contain a complicated event mix including coherent diffractive, incoherent diffractive and DIS data. An optimal simulation of this data should mix our best understanding of each of these event types and then attempt to apply the event selection criteria used by E665. This is somewhat complicated, and many comparisons to E665 μ+Pb neutron data have assumed that the Pythia mix approximates the data which does not include coherent diffraction. Since we know that the coherent diffractive events (which contribute zero neutrons per event) make up at least 13% of the E665 μ+Xe data [8], this is certainly not correct.

The phenomena of diffraction, nuclear shadowing and parton saturation are increasingly topical and important in the study and interpretation of AA, pA and potential eA data at RHIC and LHC energies. In fact they provide a lot of connections between these data sets [14]. While we now have a significantly improved Monte Carlo Model in BeAGLE, especially for describing DIS in e+A, it is clear that the diffractive physics is still not optimally modeled and further improvements are needed. Since diffractive physics is likely to be one of the physics-based design drivers for the ongoing optimization of forward detectors and their integration with the IR and the EIC machine elements for both eRHIC and JLEIC, it is important to have a complete suite of accurate eA event generators as soon as possible.

2 BeAGLE Status: Achievements through June 2018

2.1 Geometry Tagging for Incoherent Diffraction

In the most recent EIC R&D committee report [15], the following request was made concerning our ability to tag the geometry of inelastic diffractive e+A collisions. “It would be of interest in the next report to see the spectra of excitation energy and of the number of evaporated neutrons to gain an appreciation of the spread of these quantities.” The following figures satisfy that request as well as showing a comparison of the distribution of the physics variable (nuclear thickness traversed) for different choices of centrality cuts.

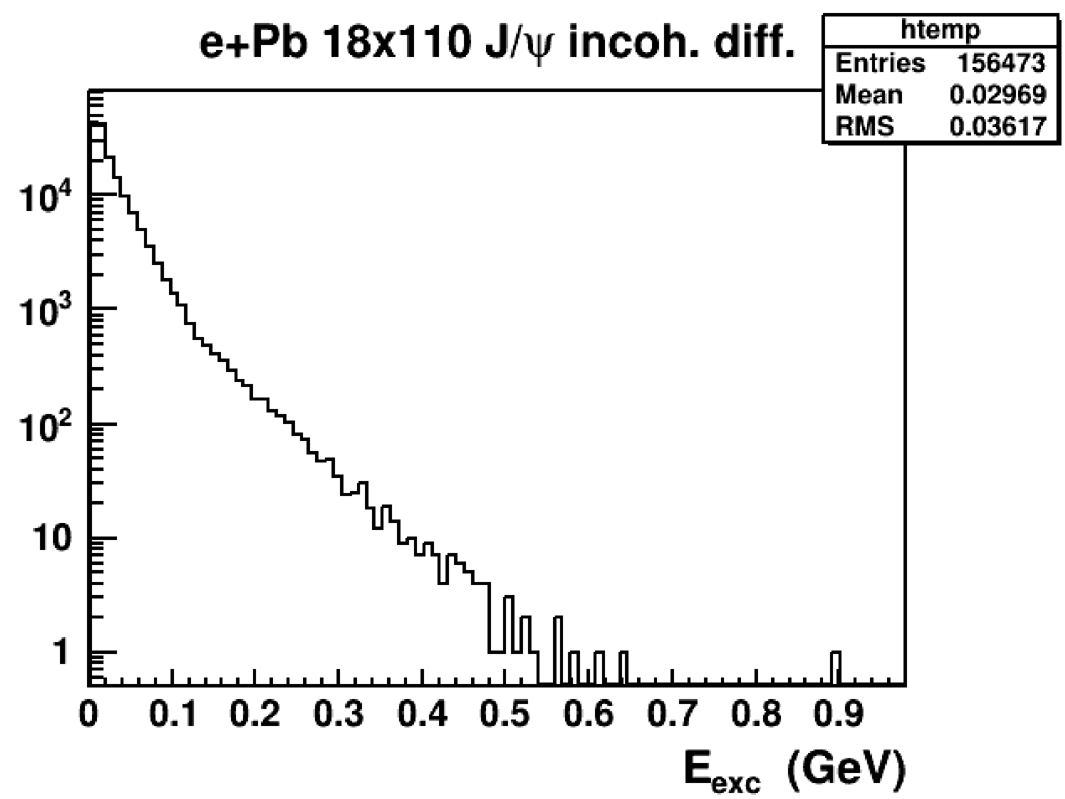
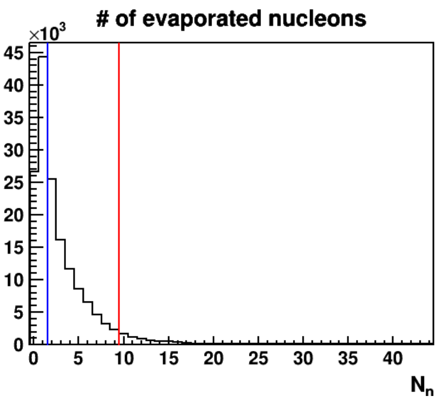
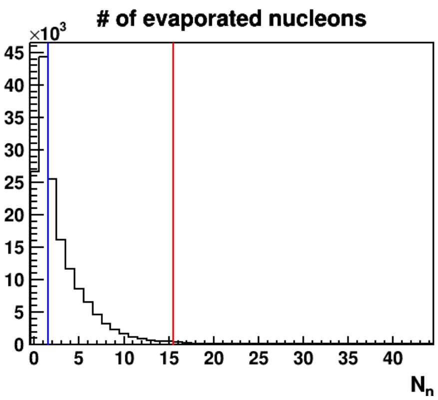


Figure 2: Distribution of the nuclear excitation energy in a BeAGLE simulation of e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events.

The current simulated data set for incoherent J/ψ e+A diffraction uses the latest beam momenta for the highest energy e+Pb collisions at eRHIC: 18 GeV for electrons and



(a) Location of peripheral and looser central cut.



(b) Location of peripheral and tighter central cut.

Figure 3: Distribution of the number of evaporation neutrons in a BeAGLE simulation of e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events with cut values indicated.

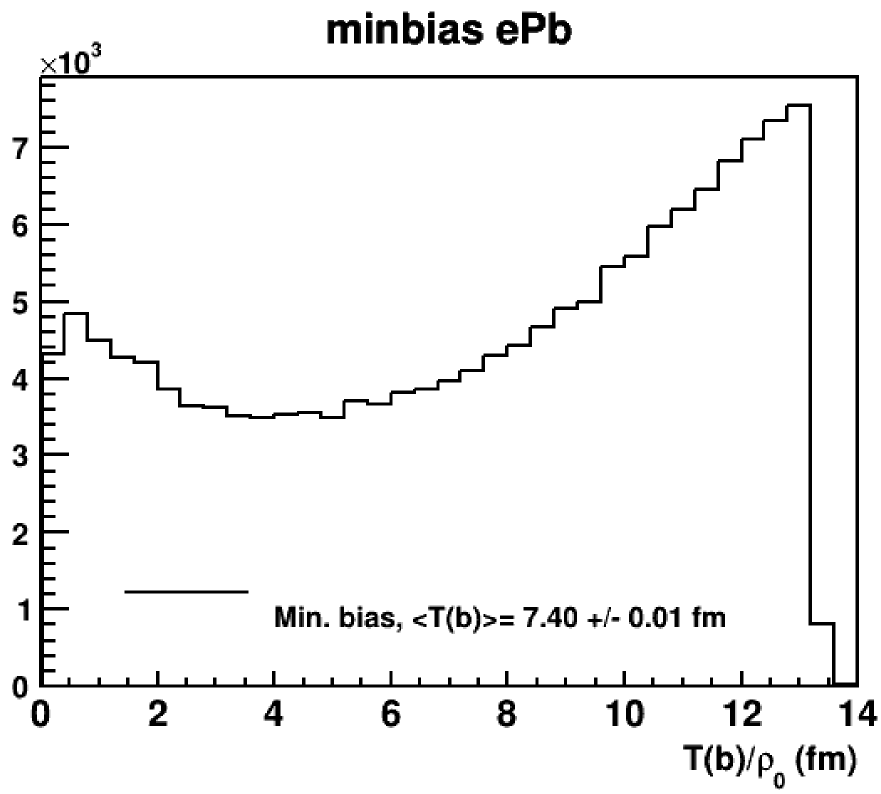


Figure 4: Distribution of the number of evaporation neutrons in a minimum bias BeAGLE simulation of e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events.

110 GeV/nucleon for Pb ions. Kinematic cuts are $0.01 < y < 0.95$, $1\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$, and $x_{Bj} < 0.01$. Our current best estimate for the range of the τ_0 INC formation

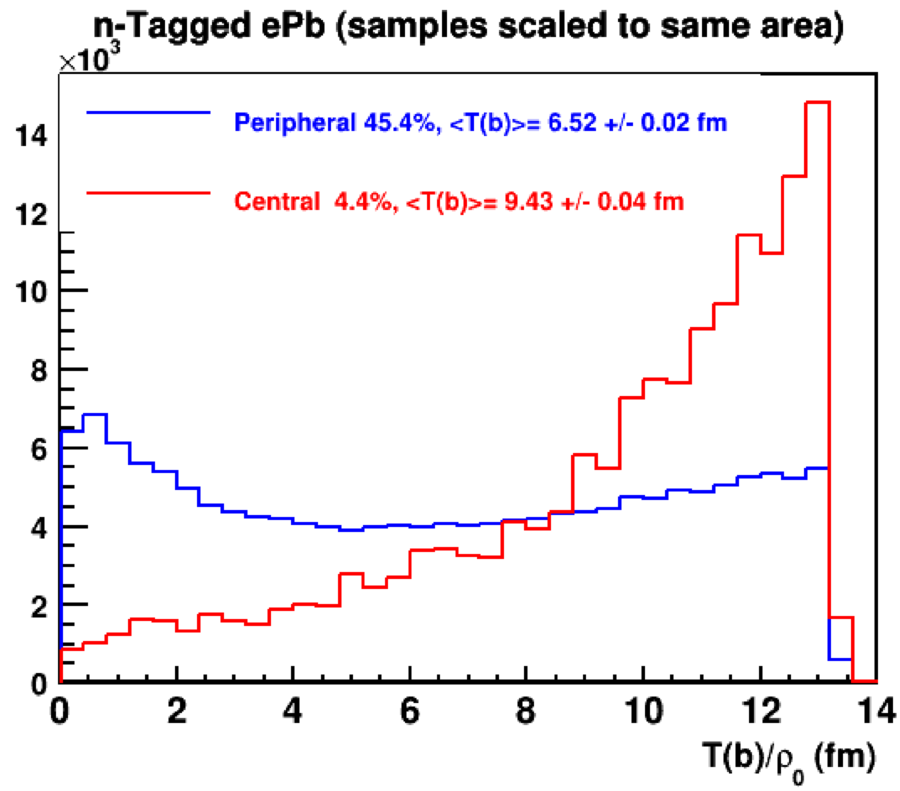


Figure 5: Distribution of the normalized nuclear thickness $T(b)/\rho_0$ for peripheral and central cuts in a BeAGLE simulation of e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events. The centrality cuts are based on the number of evaporated neutrons as shown in Figure 3a.

time parameter is 5–7 fm/c based on the E665 neutron data. The conservative value of 7 fm/c was used because that makes both the geometry and veto tagging slightly more difficult than 5 fm/c. It should be noted that these results are integrated over the diffractive momentum exchange (Mandelstam) variable t.

Figure 2 shows the excitation energy distribution. Figure 3 shows the distribution of the number of evaporation neutrons with the peripheral cut and two different choices for central cut indicated. Figure 4 shows the minimum bias distribution of the normalized nuclear thickness $T(b)/\rho_0$, where $T(b)$ is the thickness of the Pb nucleus in nucleons/fm^2 and $\rho_0 = 0.1604$ nucleons/fm^3 is the density at the center of the Pb nucleus. The result, in fm, represents the effective thickness of an equivalent slab of full-density nuclear material that you traverse.

Finally, Figures 5–6 show comparisons of the distribution of the normalized nuclear thickness for a peripheral sample with two different central samples. The saturation scale Q_s^2 should be proportional to the effective $A^{1/3}$ which is just T or equivalently T/ρ_0. The peripheral and central samples differ in thickness (saturation scale) by a factor of 1.45–1.51. In particular, the central samples significantly suppress the contribution from the "edge" of

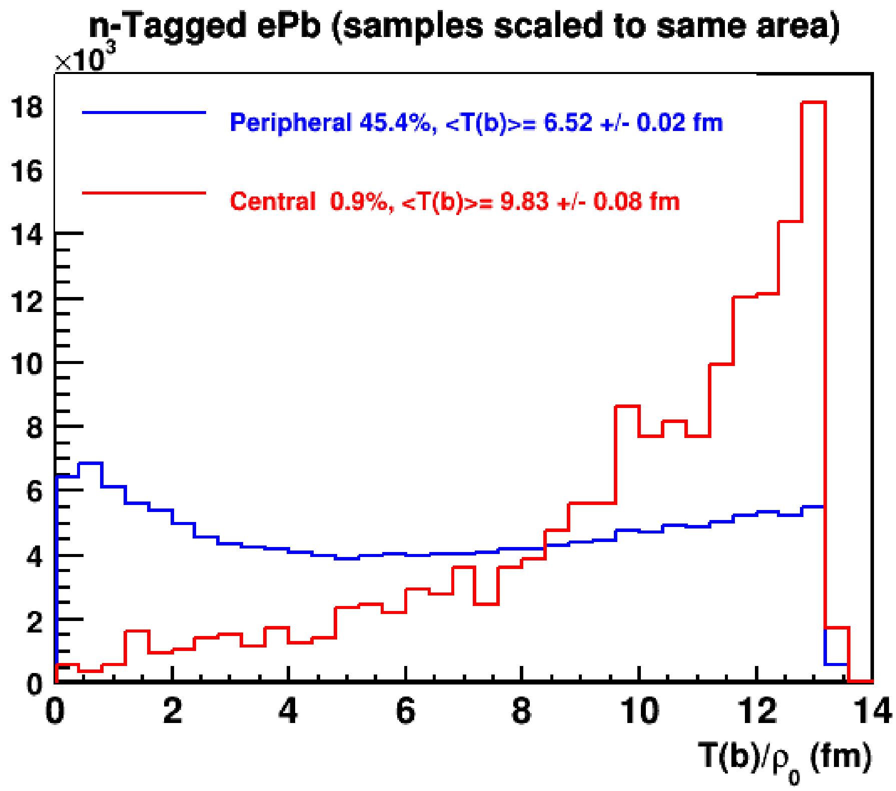


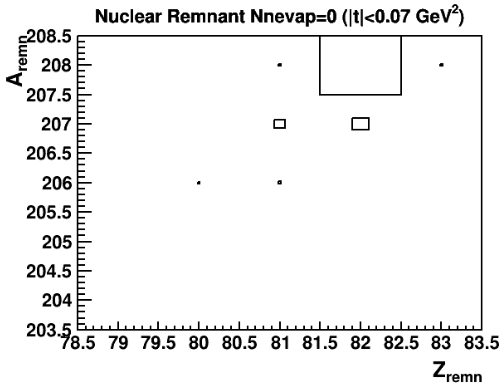
Figure 6: Distribution of the normalized nuclear thickness $T(b)/\rho_0$ for peripheral and central cuts in a BeAGLE simulation of e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events. The centrality cuts are based on the number of evaporated neutrons as shown in Figure 3b.

the nucleus (low T). The central samples are also a factor of 1.27–1.33 higher than the value (7.40 fm) of a minimum bias sample. It should be noted that it would take a beam energy (product) increase of a factor of 2.2–2.6 to achieve a similar enhancement without using geometry tagging. Further enhancement can be expected using the knockout neutrons and protons in addition to evaporation neutrons.

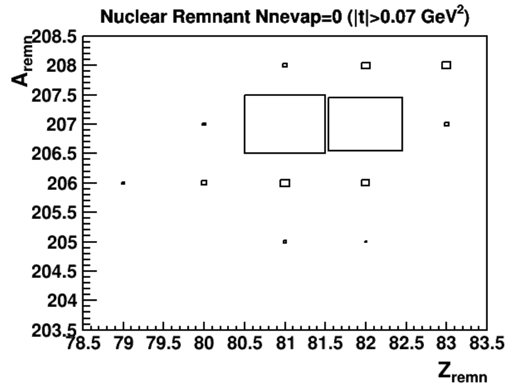
2.2 Veto Tagging for Incoherent Diffraction

As discussed above, a significant fraction of the events have no evaporation neutrons and therefore cannot be vetoed on that basis. Since the last meeting, we have further investigated our ability to use non-evaporation neutrons (knockout neutrons) as well as the photons from the de-excitation of the excited nucleus to tag the incoherent diffraction events.

Figure 7a shows that for low $|t|$ events, the collision is often soft enough so that the struck nucleon (and/or it's baryonic remnant) gets re-absorbed, leaving an excited $^{208}Pb_{82}$ nucleus, which is not excited enough to evaporate off a neutron, but which will have to



(a) Low $|t|$



(b) High $|t|$

Figure 7: Mass number (A) vs. charge (Z) for nuclear remnants in e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events in which no neutron was evaporated. The low and high $|t|$ regions are defined as below and above $|t| = 0.07$ GeV^2 respectively.

de-excite by gamma emission. Figure 7b shows that for higher $|t|$ events which nevertheless fail to emit an evaporation neutron the most typical cases involve an excited nucleus with $A = 207$ and $Z = 81$ or 82 (^{207}Tl$_{81}$ and ^{207}Pb$_{82}$). This corresponds to single-nucleon knockout: a proton or neutron respectively. In all three cases, the remnant nucleus must eventually emit photons.

The higher $|t|$ region is where the input signal-to-noise ratio (coherent/incoherent e+A diffraction) is smallest. For $|t|$ values above 0.2 GeV^2, in fact, it becomes intractable. Below that region it reaches S/N of 1/100 (second dip) and 1/430 (third dip) - see Figure 1. Fortunately, as discussed previously, simulations have shown that reconstructing the coherent result up to about 0.15 GeV^2 is sufficient to recover the input gluon distribution [10].

Figure 7b shows that it is rare for the ^{208}Pb$_{82}$ nucleus to remain intact for high values of $|t|$. This means that if we could detect the change in rigidity of the nuclear remnant due to the loss of the nucleon, we could immediately achieve the desired veto-efficiency. Unfortunately, the rigidity change between A=208 and 207 is small, typically about 1/2%, which is very challenging to detect. The possibility of adding a forward spectrometer to detect these remnants has been discussed, particularly at JLAB. Due to the technical difficulty, though, it is important to investigate other methods.

In the case of the ^{207}Pb$_{82}$ remnant, we expect the physics to be dominated by collisions where a neutron is knocked out of the original ^{208}Pb$_{82}$ nucleus by the diffractive interaction. As shown previously, only about half of these neutrons end up in the ZDC because they have a broad spread in angle θ up to about twice the size of the ZDC. We recently made an encouraging discovery, however. As mentioned above, the relevent $|t|$ range for vetoing is not really the entire $|t| > 0.07$ GeV^2 range, but rather just $0.07 < |t| < 0.15$ GeV^2 and *these* knockout neutrons *are* mostly detected in the ZDC!

Figure 8 shows the correlation between θ and t with the Fermi-momentum of the struck

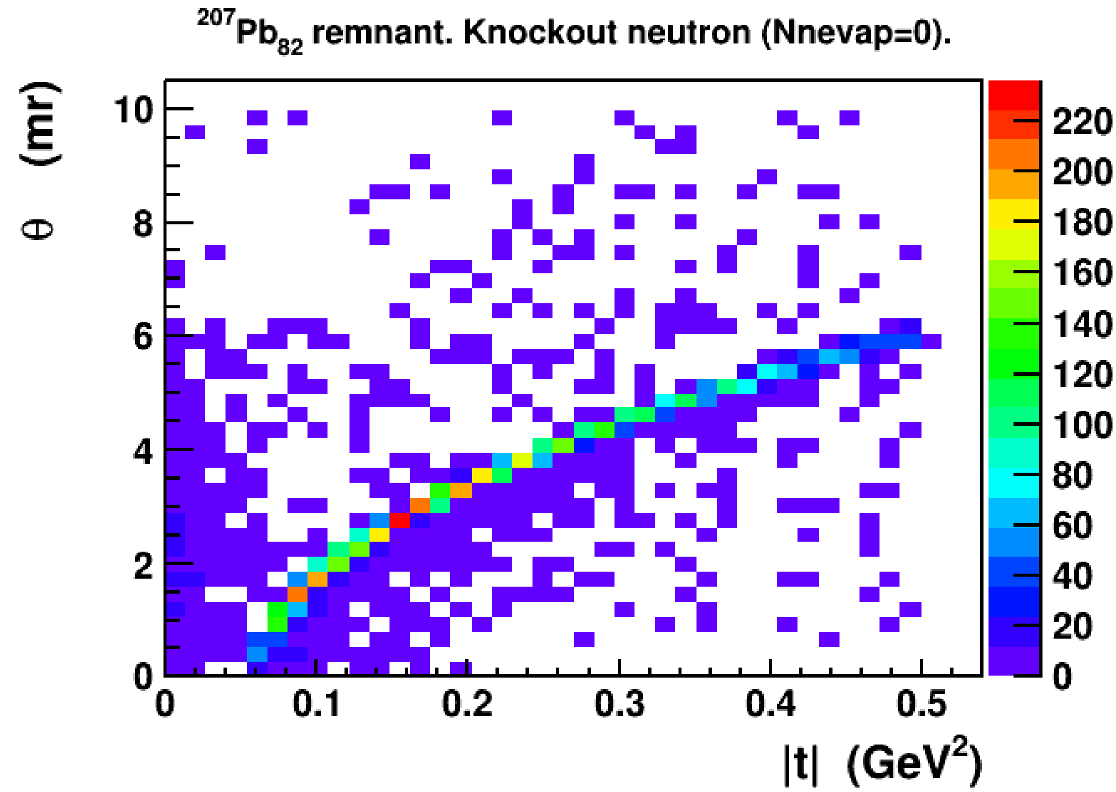


Figure 8: Correlation of the angle (θ) and $|t|$ value for knockout neutrons. Note: This simulation has suppressed the Fermi momentum for the struck neutron so the correlation is artificially tight.

nucleon suppressed (due to it not yet being properly included in the simulation!). The correlation is natural because for a free nucleon we expect $\theta \propto p_T \propto \sqrt{t}$. There is also a threshold effect due to the binding of the neutron in the nucleus. Previous plots have averaged over all values of $|t|$ up to 2–3 GeV^2, leading to an overestimate of the relevant angular spread.

Figure 9 shows an attempt to include the effect of Fermi momentum which should smear out the angular distribution. In this case the original Fermi momentum of the struck nucleon has been added back to the knockout nucleon to estimate its effect. In the future, this will be done more systematically in the simulation itself. The result is quite encouraging. We estimate a veto efficiency of about 96% from the neutrons for this subcategory of events ($N_{nevap} = 0$ and $^{207}Pb_{82}$ remnant) and when de-excitation photons are taken into account (discussed below), this rises to about 98%!

The more difficult case is the $^{207}Tl_{81}$ remnant where a proton has been knocked out. In this case there are very few neutrons ($< 1\%$). The next step is to examine the de-excitation photons. First of all, we should note that the photon energy spectrum depends on the remnant. BeAGLE, which links to the FLUKA simulation package [16], treats nuclear de-excitation very specifically, with knowledge of a few of the most likely transitions.

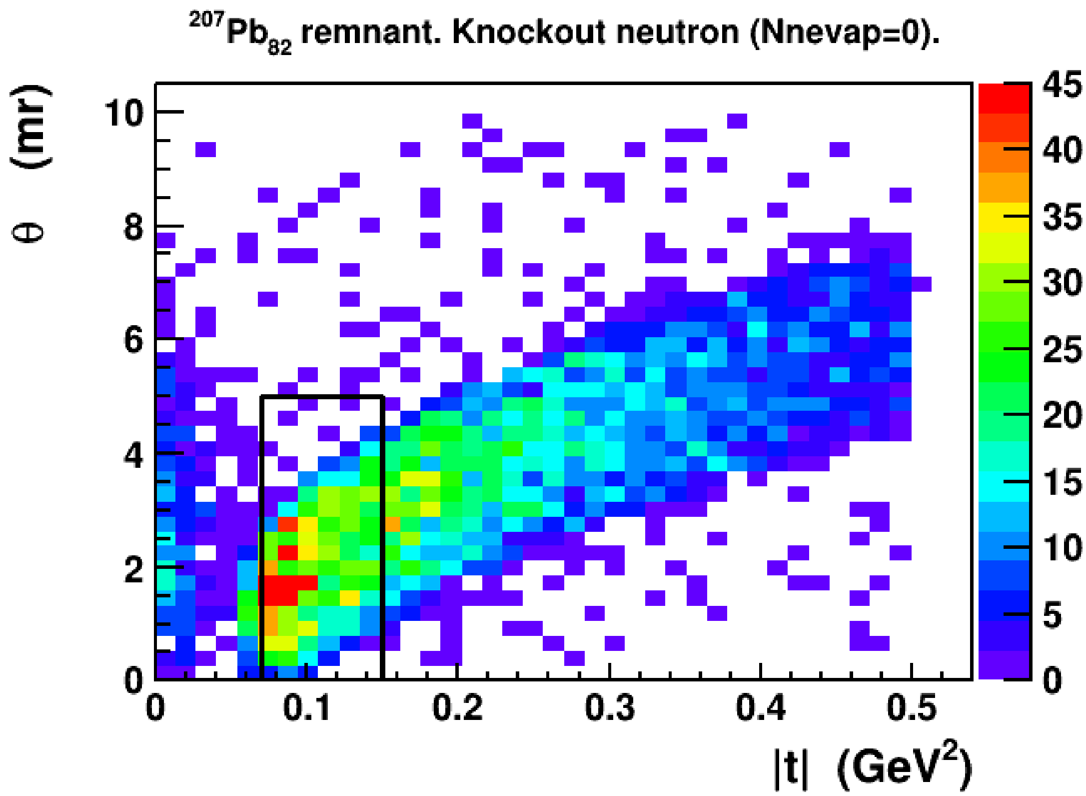
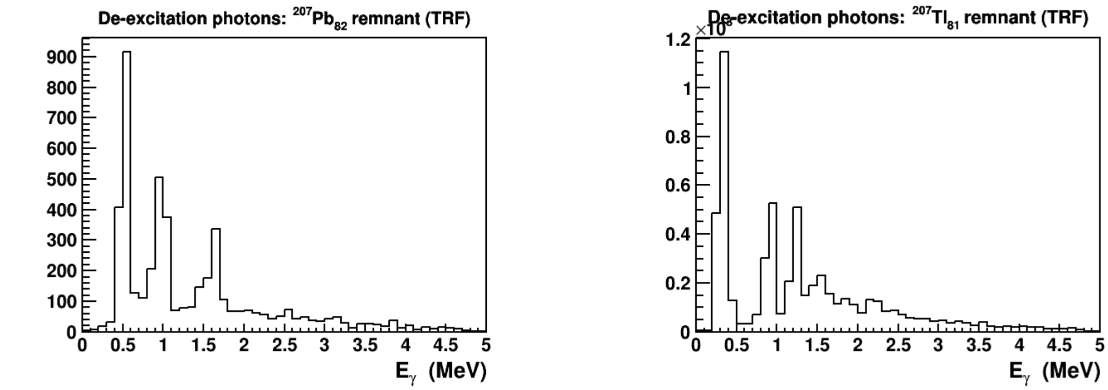


Figure 9: Correlation of the angle (θ) and $|t|$ value for knockout neutrons. In this plot the effect of the Fermi momentum has been included. The black box indicates the acceptance of the ZDC in the $|t|$ region of interest.

In all cases, the gamma emission is isotropic in the nuclear remnant rest frame. This means that half of them should be inside the forward cone $\theta < \tan^{-1}(1/\gamma)$ which is $\theta <$ 8.5 mr for 110 GeV/nucleon (eRHIC) and 23 mr for 40 GeV/nucleon (typical for JLEIC). Unfortunately these cones are larger than the respective ZDCs which cover up to 5 mr at eRHIC and 10 mr at JLEIC.

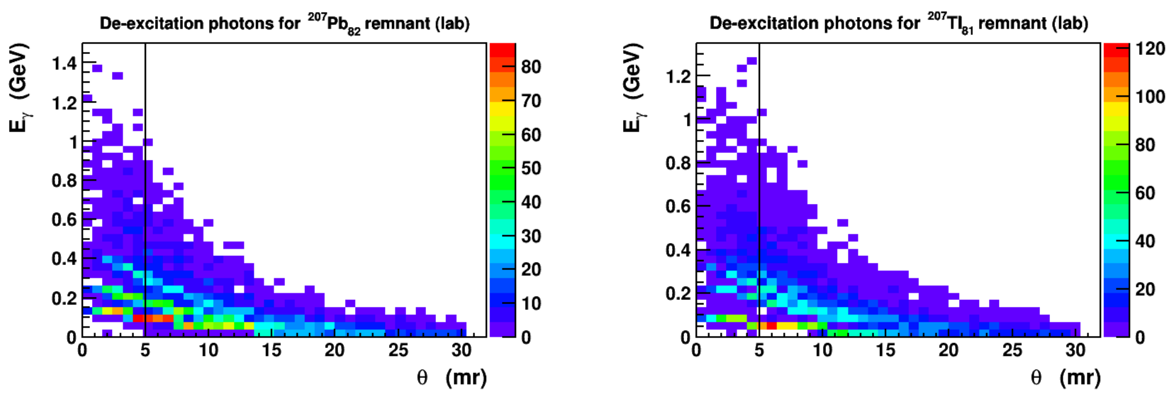
Figure 10 shows the de-excitation photon spectrum in the rest frame for the two different remnant cases that we are considering: $^{207}Pb_{82}$ where one neutron has been knocked out and $^{207}Tl_{81}$ where one proton has been knocked out. These plots should look the same for lower (JLEIC) energies. These photons are isotropic in the nuclear remnant rest frame (approximately the same as the original ion beam rest frame), and must be boosted into the laboratory (collider) frame. Figure 11 shows the angle-energy correlation for forward photons in the lab frame for the highest eRHIC energy. The events average about 3 photons each, but it should be noted that the photon angles in the lab cover the entire range from $0 < \theta < \pi$ (not shown) with the high angle (w.r.t. the ion beam) photons having low energy. Half of the photons should be in the cone $0 < \theta < 8.5$ mr.

The ZDC acceptance at eRHIC is now planned to be 5 mr (up from the previous goal of 4 mr). In principle, this cone can be instrumented to detect both 100 GeV neutron and



(a) Remnant missing one neutron. (b) Remnant missing one proton.

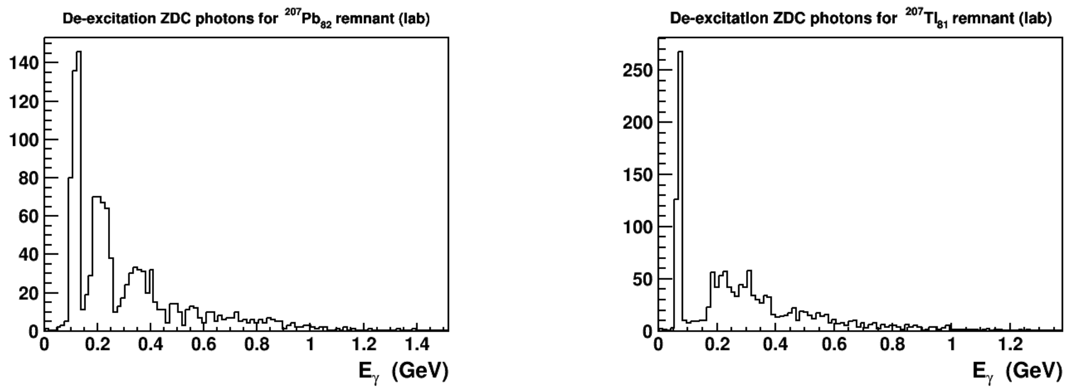
Figure 10: The photon energy spectrum from BeAGLE in the $^{208}\mathrm{Pb}_{82}$ ion beam rest frame for e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events in which no neutron was evaporated. The two cases shown are a) nuclear remnant $^{207}\mathrm{Pb}_{82}$ where one neutron is missing from the original nucleus and b) nuclear remnant $^{207}\mathrm{Tl}_{81}$ where one proton is missing from the original nucleus.



(a) Remnant missing one neutron. (b) Remnant missing one proton.

Figure 11: The correlation between photon angle and energy for forward photons from BeAGLE in the laboratory collider frame for e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events in which no neutron was evaporated. The two cases shown are a) nuclear remnant $^{207}\mathrm{Pb}_{82}$ where one neutron is missing from the original nucleus and b) nuclear remnant $^{207}\mathrm{Tl}_{81}$ where one proton is missing from the original nucleus. The line at 5 mr corresponds to the edge of the planned ZDC at eRHIC.

100 MeV photons. Figure 12 shows the spectrum of photon in that ZDC acceptance. For the neutron-knockout events (a), if we assume a minimum γ energy threshold of 100 MeV, then basically the entire spectrum is accepted if it is forward enough. This leads to a probability of catching a photon of about 50%, raising the overall probability of detection



(a) Remnant missing one neutron.

(b) Remnant missing one proton.

Figure 12: The de-excitation photon spectrum for forward photons hitting the ZDC acceptance ($\theta < 5$ mr) from BeAGLE in the laboratory collider frame for e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events in which no neutron was evaporated. The two cases shown are a) nuclear remnant $^{207}\mathrm{Pb}_{82}$ where one neutron is missing from the original nucleus and b) nuclear remnant $^{207}\mathrm{Tl}_{81}$ where one proton is missing from the original nucleus.

of from 96% (based on knockout neutrons alone) to about 98%. This is a 98% chance of detecting a neutron knockout event that fails to evaporate any neutrons in addition.

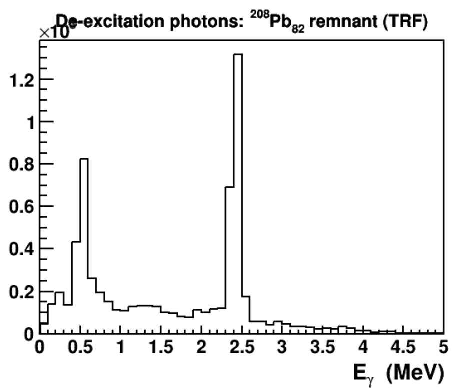
The difficult case, based on neutral detection alone, is then the proton-knockout events. Very few ($< 1\%$) of these events show a forward neutron, so we rely on the photons. Figure 12(b) shows the spectrum for these events, which unfortunately, includes a spike at about 75 MeV. Depending on whether we can detect these above background cuts or not, our efficiency for catching at least one photon in these events is either 57% or 46%.

Assembling all of these cases, if we start with 8238 simulated 18x110 e+Pb diffractive J/ψ events in the range $0.07 < |t| < 0.15$ GeV^2 we end up with about 250–300 events with no neutrons or photons hitting the ZDC. This corresponds to an overall veto rejection factor of 28–34 or about 30, compared to our goal of 100–1300. The vast majority of these events are those where one proton was knocked out of the nucleus, and, like the neutrons, these are forward focused and should be detectable with reasonable efficiency. If we can also detect these events with 98% efficiency, then the OVERALL veto rejection factor, including the evaporation neutrons, will be about 400 (99.75% efficiency).

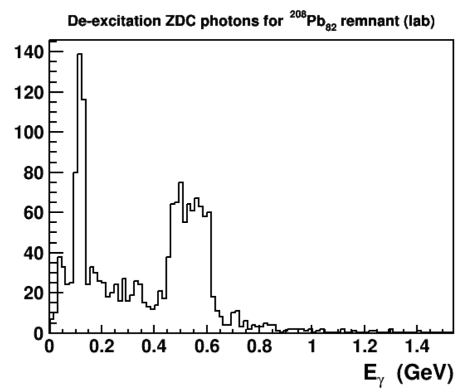
In conclusion, a 5 mr ZDC at eRHIC, even with photon capability, is not sufficient to veto incoherent diffraction events at the desired efficiency. Forward proton detection (or the more difficult detection of (A-1) remnants) is also needed. The good news is that the planned forward proton detection may be sufficient to close the gap. More studies are needed as well as improvements to the Fermi-momentum handling and the modeling of the hard diffractive subevents (i.e. eN in RAPGAP). The results for JLEIC should be qualitiatively similar, although the photon detection above background will be more challenging due to the reduced boost.

The low $|t|$ case is quite complicated and has not yet been looked at in detail. Even though it represents a narrow slice of t, it has to be studied as a function of t because important features are varying rapidly: coherent/incoherent ratio (pre-veto signal-to-noise), the neutron evaporation probability, and the excitation energy which determines the amount of gamma de-excitation needed. In addition, when the Fermi momentum is properly included in the simulation, there should be an increased probability of nucleon knockout, again as a strong function of $|t|$.

Another interesting difference for the low $|t|$ case is the fact that the $^{208}Pb_{82}$ nucleus has a subtantial energy gap between the ground state and the excited states. This means that an incoherent collision which results in an excited $^{208}Pb_{82}$ nucleus should have at least one relatively high energy photon (> 2 MeV in the nuclear rest frame), but it will also have fewer photons per event (about 2 on average).



(a) Photon energy in the nuclear rest frame



(b) Photon energy in the ZDC acceptance in the lab frame

Figure 13: De-excitation photon spectra for excited $^{208}Pb_{82}$ in the for e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events in which no neutron was evaporated. The spectra are shown in two cases: a) the ion beam rest frame b) the laboratory frame for forward ($\theta < 0.005$ rad.) photons only.

Figure 13a shows the photon spectrum in the ion rest frame for the de-excitation of $^{208}Pb_{82}$. Figure 13b shows the spectrum in the lab frame for photons which hit the ZDC for the highest eRHIC energy. The photons are a lot harder than for the $A = 207$ nuclei. Figure 14 shows the correlation between angle and energy of these photons in the lab frame.

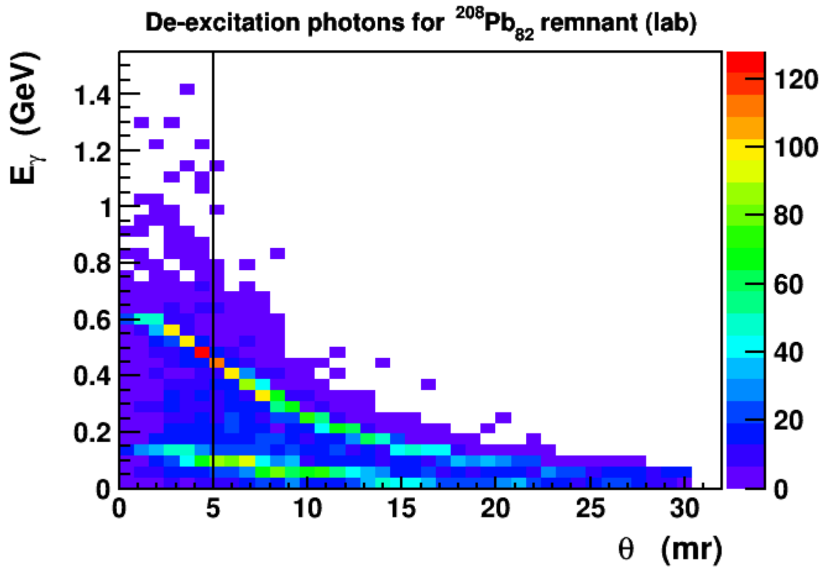


Figure 14: Correlation of the photon energy (E) and angle (θ) for forward photons in the lab frame for e+Pb 18x110 GeV/nucleon incoherent diffractive J/ψ events in which no neutron was evaporated.

2.3 FY2018 Technical Progress and Timetable

Table 1 is an update of the standard eRD17 Status Report table. The main accomplishment during the reporting period is that the BeAGLE and RAPGAP have been successfully linked together using 64-bit libraries (α test version item 19a). The main challenge here was that both programs already link to a lot of libraries and read/write to a lot of individual logical unit numbers, so minor inconsistencies and overlaps had to be dealt with. BeAGLE now has the capability to generate RAPGAP e+p simlulated data which is identical to that produced by standalone RAPGAP when started with the same random number seed. The code is easily switched between this mode and the standard running mode using PYTHIA. The next steps will involve embedding the RAPGAP e+p collisions in the BeAGLE/DPMJET e+A collisions and applying the standard nuclear effects (items 19b-c: β release and final release).

In installing RAPGAP, a new issue became clear. Unlike PYTHIA, RAPGAP does not naturally have a provision for e+n collisions, only e+p as well as p+p. Fortunately, Hannes Jung, the author of RAPGAP is actively engaged and interested in working himself to help us implement this capability. It involves three pieces, none of them conceptually difficult:

1. Use isospin flipped ($u \leftrightarrow d$) parton distribution functions.
2. Ensure the correct nucleon beam remnant.
3. Use correct masses consistently everywhere.

Item 1 on this list is straightforward as we already do this for Pythia in BeAGLE. Item 2 is also not too difficult as Pythia is setup to do this and RAPGAP uses Pythia routines for beam remnants. Item 3 is conceptually not difficult, but will take some care to find all of the places where the proton mass is hard-coded. Experience indicates that there is no room for mixing up the neutron and proton masses. All in all, this should not be too difficult, but it will probably force us to wait until January to have a fully functional BeAGLE/RAPGAP including interchangeable e+p and e+n subcollisions. This project has been added as item 19d in the table. It should be noted that once we have the fully functioning BeAGLE/RAPGAP using the current (e+p only) RAPGAP, we will already be able to compare BeAGLE/RAPGAP and BeAGLE/PYTHIA to understand the differences. BeAGLE already has the capability (for testing purposes) to ensure that the e+N hard subcollision is always e+p or alway e+n or an appropriate mix.

There were some smaller accomplishments during the reporting period. Baker spoke at the POETIC8 Monte Carlo Event Generator Workshop (co-organized by Aschenauer) in March 2018. BeAGLE was well received[1] and we learned a lot about other e+A MCEG efforts for possible future comparison or collaboration. It seems clear that nobody else is quite ready to tackle the forward detector / incoherent diffraction veto issue in the near future. We are also seeing expanding interest in BeAGLE as two new groups at JLAB have expressed interest in using BeAGLE. We also added an important capability

[1] Except at least one person didn't like the name, which was a surprise!

Feature added or error corrected	BeAGLE 12/2017	BeAGLE 6/2018	BeAGLE (planned)
1-8. Early BeAGLE features (see text).	YES	YES	YES
9. Shadowing coherence length	NO	NO	YES
10. Partial shadowing effect	YES	YES	YES
11a. Effective σ_{dipole} for J/ψ averaged over x & Q^2	YES	YES	YES
11b. Effective σ_{dipole} for ϕ averaged over x & Q^2	YES	YES	YES
11c. Eff. $\sigma_{dipole}(x,Q^2)$ for $V=\psi,\phi,\rho,\omega$ from Sartre (ePb)	NO	NO	YES
11d. Use correct $R_{diff}^{(A=208)}(x,Q^2)$ for V from Sartre	NO	NO	YES
11e. Improved σ_{dipole} for V, if necessary	NO	NO	YES
12. Tune to E665 μA Streamer Chamber data	NO	NO	YES
13. FS p_F for hard process correct	(Testing)	Partial	YES
14. Kinematic matching between DPMJet&Pythia	YES	YES	YES
15. Protect against very high E* values.	YES	YES	YES
16. Enable nPDF with any value of A,Z (EPS09)	YES	YES	YES
17. Extend R→ σ_{dipole} map to more values of A	NO	NO	YES
18. Tune the t distribution for multiple scattering.	NO	NO	YES
19a. Release α version BeAGLE/RAPGAP	NO	YES	YES
19b-c. Install, test, & release BeAGLE/RAPGAP	NO	NO	YES
19d. Extend RAPGAP to include e+n (w/ H. Jung)	NO	NO	YES
20. Allow diffraction w/ individual $V=\psi,\phi,\rho,\omega$	NO	YES	YES
21. Cleanup and document BeAGLE work so far.	NO	NO	YES
XX. Implement UltraPeripheral Photon Flux	NO	NO	???
XX. Tune BeAGLE to UPC data (RHIC &/or LHC)	NO	NO	???

Table 1: Technical Progress / Plans for eRD17

to BeAGLE, allowing us to create diffraction events using any of the four available vector mesons: J/ψ, ϕ, ρ, ω. The existing Pythia code only allowed us to use all of them or none of them, which was not optimal as the ψ and ϕ are the rarer ones. This was added ex post facto as item 20 in the table.

In summary, substantial progress has been made in this reporting period. BeAGLE is being used at both BNL and JLAB and its use is expanding. We have advanced our understanding of veto tagging with encouraging results. BeAGLE and RAPGAP have been linked together without any major problems. The remaining tasks to be completed will be detailed below in Section 3.

2.4 Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project.

The only funded manpower consists of Baker, who has spends 0.25 FTE on the project.

Zheng contributed a significant amount of effort, about 0.1 FTE-year already in consulting on technical questions, running simulations, and making plots.

Aschenauer and Lee have participated in meetings and contributed advice.

3 Immediate Plans

The main and highest priority activity planned for the remainder of FY2018 is to finish the implementation of RAPGAP into BeAGLE in the e+p hard subevent incarnation (item 19b–c). In addition, we should complete the iterative post-fix of the missing Fermi momentum for the struck nucleon (item 13). Finally we should extend the dipole cross-section map to include more values of A, in particular Xe and one light ion such as C (item 17).

The main tasks involved in the RAPGAP integration (item 19b–c) are:

- Output the RAPGAP event in BeAGLE format rather than RAPGAP format. Internally to the code, this also involves transferring the events from the Pythia common block (used by RAPGAP) to the DPMJET common block (used by BeAGLE).
- Embed the RAPGAP e+p event in the BeAGLE (DPMJET) e+A event, applying Glauber multiple scattering, intranuclear cascade and nuclear breakup/evaporation steps.
- Search through RAPGAP code for inconsistent kinematic approximations.

The first two of these steps are very straightforward due to the fact that Pythia and RAPGAP use the same data structure (the Pythia common blocks). The kinematic approximation is also straightforward, since we have experience, but may take some time.

Item 13, "FS p_F for hard processes correct" refers to fixing a problem in the original DPMJetHybrid/BeAGLE implementation. Due to the way Pythia is initialized in BeAGLE, all of the hard $e + p$ and $e + n$ collisions are treated with the proton and neutron at rest in the nuclear rest frame, ignoring the fact that they should have some Fermi momentum. We essentially take a slightly moving nucleon in the initial Glauber configuration of the ion A and replace it with the contents of the Pythia final state, thereby throwing away it's initial state momentum. Fixing this involves writing a routine to reapply the original struck nucleon four-momentum back into the γ^*+N subevent from Pythia where it was discarded. This can then be applied to the partonic skeleton before fragmentation. This works fine for the case when there are only two outgoing particles (e.g. J/ψ+n or quark+diquark), because the math is exact, but some approximations were needed in the multibody case which proved to be destabilizing. Some time was wasted trying to find better mathematical approximations. In the end, it will be straightforward to apply the extra four-momentum in an iterative procedure.

Item 17 just requires us to run the standalone Glauber code TGlauberMC [17] with more settings.

4 Proposal for FY2019

The proposed main goals for FY2019 are to complete the upgrade of BeAGLE, using a better description of diffraction; to clean up and document the code; and to make a concerted effort to tune BeAGLE, as well as possible, to the relevant data from E665, in particular including the event-by-event hermetic streamer chamber μ+Xe data. This will provide the community with a unique, calibrated tool to best understand incoherent exclusive vector meson production through diffraction in e+A collisons, as well as DIS. This physics is a key EIC measurement in its own right and is also the main background to another key EIC measurement: *coherent* exclusive vector meson production through diffraction in e+A collisions. Coherent production itself would not be directly included in BeAGLE, but it would be straightforward to mix background events from BeAGLE with coherent events from Sar*t*re and then present those events to GEMC (JLAB) or eicroot/eic-smear (BNL) in order to understand the effect of the detector design on the measurement.

This project is essential and timely because BeAGLE remains one of our best tools to simulate e+A collisions at an EIC in order to estimate the physics reach and to understand the forward detector & IR requirements as well as the tradeoffs between physics reach and detector/IR considerations. Nevertheless, conclusions from studies using BeAGLE contain one key assumption which rests on a limited amount of not fully understood data. In particular, the event-averaged neutron multiplicity from E665 μ+Pb data [7] was lower than originally expected, which suggests a reduced amount of intranuclear cascading (INC), implemented in BeAGLE as a relatively long formation time (τ_0) for produced particles from the hard collision. This line of reasoning in indirect in two ways. First, we have to estimate, rather than measure, the relative amount of coherent diffraction, incoherent diffraction and DIS in the E665 data, leading to an uncertainty in the correct τ_0 parameter. Second, the observed neutrons primarily come from neutron evaporation after the collision is over and we do not directly measure the INC products. We are assuming that a reduction in INC products leads to a reduction in nuclear remnant excitation which, in turn, leads to a reduction in neutron evaporation.

Adding RAPGAP as an option in BeAGLE as well as tuning to the fixed target E665 Streamer Chamber data [8] will improve this situation dramatically. The E665 Streamer Chamber data measures almost all charged particles coming from the collision including most of the INC products directly [2]. This will allow us to confirm that the modest amount of evaporation is due to a modest amount of INC. Also the data are reported event-by-event so distributions in multiplicity and rapidity gap will allow us to directly constrain or tune the relative amount of different event classes (DIS vs. diffractive etc.).

This goal is almost the same as what was presented a year ago except for two changes. We have extended the inclusion of RAPGAP into BeAGLE by three months (to January) in order to include e+n collisions into RAPGAP and to cleanup and document BeAGLE. BeAGLE is beginning to be used more broadly and the documentation should be updated to reflect all of the changes. The cleanup refers to the removal of unused code and also skipping or removing unnecessary code from unused DPMJET options. The second major change to our goals since last year is that we have postponed the implementation of ultra-peripheral A+A collisions and tuning to ultraperipheral collisions. While useful, this goal is significantly less direct than using the E665 SC data and detracts from our main focus at this time.

4.1 Personnel, Timetable and Budget

The goal for FY2019 remains to upgrade BeAGLE to include RAPGAP (extended to include en), to make any necessary improvements to BeAGLE's multiple scattering model (items 9,11,18 in Table 1) and to tune BeAGLE to the E665 Streamer Chamber data as well as the E665 neutrons, while preserving the agreement with HERA e+p data on forward protons, forward neutrons and J/ψ production. This will include a rough simulation of the E665 trigger and event selection for the two papers as well as an estimate using Sar*t*re and Pythia(BeAGLE) of the relative cross-sections of DIS, incoherenet diffractive and coherent diffractive events. In order to optimize for this goal, we have postponed any work on ultraperipheral collisions for now.

Estimated milestones for these tasks are:

Jan. 15, 2019 BeAGLE cleanup and full RAPGAP installation (includes e+n) Process-dependent dipole cross-section implemented in BeAGLE

May 31, 2019 Compare BeAGLE to E665 data using our best current information.

Sept. 30, 2019 Tune BeAGLE to the data to our best ability.

We are also proposing travel money for Liang Zheng to visit BNL for a month during the summer of 2019. This will be ideal timing as we will be working on tuning to the data at that time and frequent and close communication will be especially valuable. This is

[2]Very low momentum particles as well as the heavy nuclear remnant and most light ions will be absorbed in the target or other material.

Person	Institution	Effort (FTE-year)	Cost to Proposal	Remarks
E. Aschenauer	BNL	0.05	$0	cost covered by BNL
M.D. Baker	MDBPADS[18]	0.25	$62,400	
J.H. Lee	BNL	0.05	$0	cost covered by BNL
L. Zheng	CUGW	0.10	$0	cost covered by CUGW
TOTAL:		0.45	$62,400	

Table 2: Personnel Budget Breakdown for FY2019

Item	Cost
Personnel:	$62,400
Zheng Travel	$4,500
Other Travel	$1,500
TOTAL:	$68,400

Table 3: Total Budget Breakdown for FY2019

estimated to cost about $4500 (direct). In addition we are asking for $1500 for a possible domestic trip for Baker to a meeting or for some other experts to visit BNL.

Table 2 shows the personnel budget breakdown for FY2019 which is identical to the FY2018 budget plus inflation. Table 3 shows the total budget, including the new budget item: travel funding. Internet connection to China is still very poor (large lag times) and Liang is also very busy as a new professor. A dedicated period of focused effort at BNL during the summer of 2019 should be very valuable.

4.2 Impact of Reduced Funding

Table 4 shows the impact of reduced funding. With full funding we expect to complete the project — using E665 SC data to tune and validate BeAGLE — providing the community with a version of BeAGLE which will be optimal for understanding the tradeoffs between the completeness and quality of forward detection on the one hand and important physics goals. At the 80% funding level, we will significantly reduce the chances of project completion in FY2019. It would only be possible if we are extremely lucky and everything goes unusually well. Most likely the project would have to be extended into FY2020. At the 60% level, the project will almost certainly take an additional year.

Funding Level	%Funding	Baker FTE	Travel	Project Completion
$68,400	100%	0.25 FTE	$6000 Liang+other	FY2019
$54,720	80%	0.20 FTE	$4500 Liang only	May extend into FY2020
$41,040	60%	0.16 FTE	$0 No travel	FY2020

Table 4: Impact of Reduced Funding in FY2019

Having a validated version of BeAGLE as soon as possible is very important. Both laboratories are already preparing their "pre-CDRs" and it is urgent to understand how well the current designs work for the critical physics goals of the e+A part of the program.

5 External Funding

5.1 FY2018

During FY2018, Aschenauer, Lee, and Zheng's salaries were provided by their home institutions.

Baker and Zheng participated in a JLAB LDRD "Geometry Tagging for Heavy Ions at JLEIC" (V. Morozov et al.) [19] in FY2017-FY2018. One important new feature was added to BeAGLE: the capability of handling nonspherical nuclei (such as e+U collisions). Physics studies at JLEIC energies are ongoing, but this project will be officially complete at the end of FY2018.

5.2 FY2019

During FY2019, Aschenauer, Lee and Zheng's salaries are expected to still be provided by their home institutions.

Baker and Zheng and collaborators (D. Higinbotham et al.) have proposed a new JLAB LDRD for FY2019-2020, which is orthogonal to the EIC R&D proposal. The main thrust of the JLAB proposal is to extend BeAGLE to include short range nucleon-nucleon correlations in the nucleus. This leads to long tails in the Fermi momentum of the struck nucleon as well as a correlated spectator partner. In addition, this effort would include an overhaul of the Fermi momentum in BeAGLE. The magnitude and shape of the distribution will be better matched to data and the Fermi momentum will be applied *before* the hard e+N collision, obviating the need to "post-fix" the momentum non-conservation. This proposal has not yet been decided upon by JLAB management. If approved, the JLAB LDRD work will be synergistic with eRD17, but is explicitly designed to not duplicate effort.

6 Summary

The BeAGLE program for simulating e+A collisions is now being used at both prospective host laboratories for physics-driven refinement of detector requirements, particularly in the forward region. As discussed in the last two meetings, we have discovered that a key EIC physics measurement, incoherent diffractive exclusive vector meson production in e+A collisions, is likely to be an important driver of forward detector requirements, but is not yet well simulated. This measurement, especially in the case of ϕ production, is sensitive to gluon saturation. The process, especially in the case of the J/ψ, is also a background to coherent production, which would allow the measurement of the transverse spatial gluon distribution along with saturation effects.

We therefore proposed, in FY2018-2019, to extend BeAGLE to better describe diffractive physics in e+A collisions. We have made significant progress and are on track to complete the project in FY2019, providing the community with a significantly improved and validated e+A model code. Given the ongoing detector and machine design optimization, this project is urgent and should not be delayed.

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