PHENIX

PX No. 209 BNL No. 69035

Photon-Hadron Interactions at RHIC and LHC Energies

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Proc. of the Recontres de Moriond "QCD and High Energy Hadron Interactions",
Les Arcs, France
March 2001

Physics Department

Brookhaven National Laboratory
Operated by
Brookhaven Science Associates
Upton, NY 11973

Under Contract with the United States Department of Energy
Contract Number DE-AC02-98CH10886

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Heavy Ion Collisions at RHIC and LHC energies are potentially an interesting laboratory for the study of QED. In these collisions, a Heavy Ion in one beam sees a highly Lorentz contracted electric field due to an oncoming beam particle. The Electric field reaches a maximum value of E$\simeq \gamma_{eff} \cdot Z \cdot e/b^2$, where the apparent Lorentz factor, γ_{eff}=$2 \cdot \gamma_{beam}^2 - 1$. The collision may be viewed in terms of a flux of photons colliding with a stationary ion target using the equivalent photon approximation, originally introduced by Fermi in 1924. We show that the cross section for Inelastic Electromagnetic Interactions of Heavy Ions are both calculable and have been measured in the first RHIC running period.

1 Introduction

An interesting aspect of the Relativistic Heavy Ion Collider(RHIC) is the high rate of $\gamma - \gamma$ and γ-hadron collisions it produces. For example, under nominal Au-Au running conditions the γ-nucleus luminosity is $\sim 10^{29} cm^{-2} \cdot s^{-1}$ for equivalent photon energies with 2 Gev$\leq E_\gamma \lesssim 300$ GeV. How do Heavy Ion colliders like RHIC and LHC compare as γ-hadron colliders with high energy lepton-hadron collisions potentially available in the laboratory? How about with High Energy γ's from extra-terrestrial sources?

It is interesting to note that Fermi's original paper[1], which introduced the method of equivalent quanta dealt with both electron and Ion(α-particle) interactions with matter. In order to compare RHIC with an equivalent electron-Ion Collider(eIC), I consider the case of electron-Ion colliders under discussion at BNL and DESY, specifically the parameters of the eIC[2] with a high brightness 10 GeV electron beam colliding with the RHIC Ion beams. The equivalent photon flux may be expressed, to good approximation, as follows[3]

$$\omega\frac{dN(\omega)}{d\omega} = \frac{2\alpha \cdot Z^2}{\pi} ln(\frac{\hbar\gamma_{eff}}{b_0\omega}) \times 2, \quad \omega\frac{dN(\omega)}{d\omega} = \frac{2\alpha}{\pi} ln(\frac{m_e\gamma_{eff}}{\omega}) \tag{1}$$

for the ion and electron case,respectively. The last factor of 2 in the former is due to the fact that both beams are intense photon sources. The logarithms arise from integrals over photon q^2 which, in the e-Ion case, I arbitrarily take to be $\leq 2m_e^2$. In the Heavy Ion case the upper cutoff on q^2 arises from coherence considerations. In Fig. 1 I assume the nominal RHIC and LHC energy and nuclear species. When actual beam parameters are considered it turns out that eIC and RHIC have very similar γ-hadron collision rates. It's interesting to note that the endpoint of the LHC spectrum is not very different from the theoretical end-point of the very highest energy Gamma ray component of cosmic rays ($\simeq 10^{13-14}$ eV). So effectively LHC will produce the highest energy γ-hadron collisions on the planet.

The question naturally arises whether one can make use of the opportunity to study these electromagnetic interactions with Ion beams. The answer is that the first steps have already

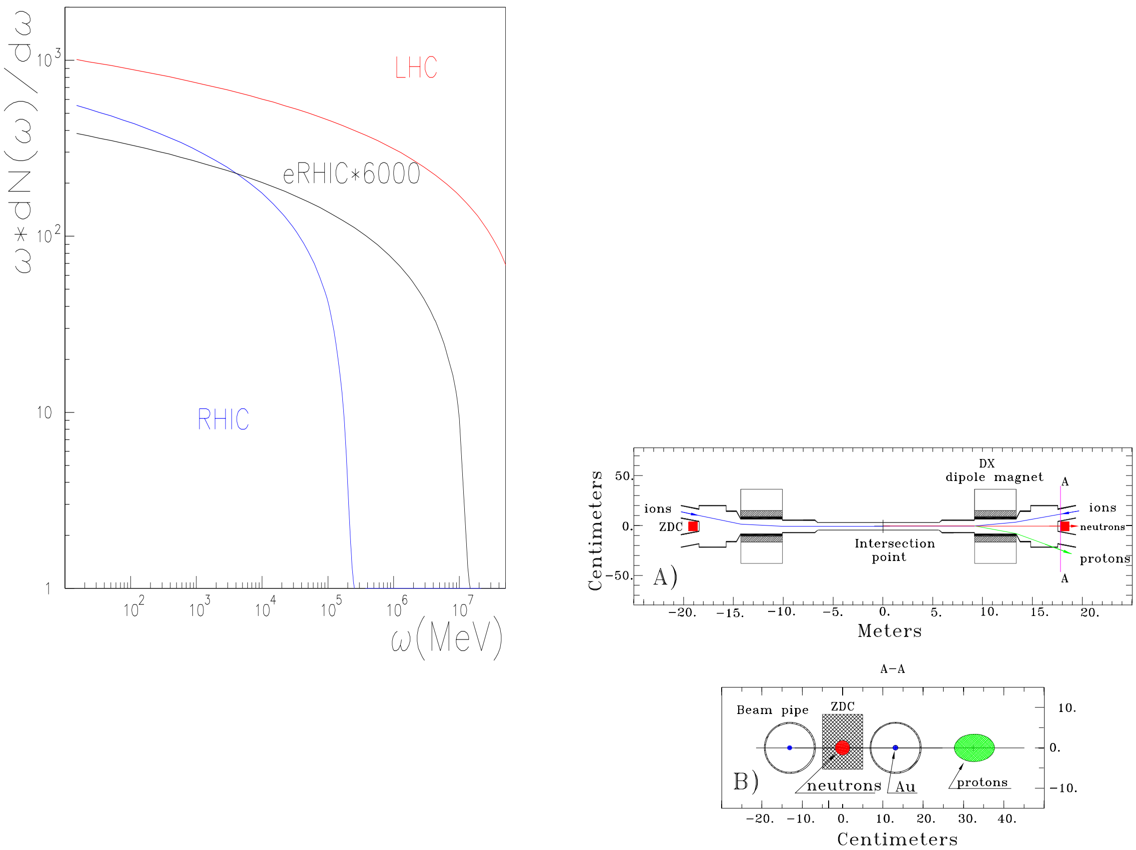

Figure 1: Comparison of Heavy Ion Colliders with a e-Heavy Ion collider. Layout of PHENIX detectors and interaction region(right panel).

been taken with the first data from RHIC. Here we discuss the large, total cross sections as an example. We will see that the calculations and first measurements are in good agreement.

2 The Total Inelastic cross section

The process of electromagnetic dissociation is a well-known feature of heavy ion collisions. For those collisions where the impact parameter is larger than the sum of the nuclear radii, one nucleus may, nevertheless, undergo interaction with the intense electric field of the other nucleus. This process is described in terms of the Weizsäcker-Williams formalism and is typically dominated by the large photonuclear cross-section at the Giant Dipole Resonance from equivalent photons with energy, $E_\gamma < 24$MeV.

The cross-section for the above reaction ("single beam dissociation") is quite large[4] (95 barns for $\sqrt{s_{NN}} = 200$ GeV Au beams) and will ultimately limit beam lifetime at RHIC. Mutual Coulomb Dissociation (MCD), whereby both beam nuclei dissociate electromagnetically, was first studied because of its potential use for luminosity monitoring at RHIC [5,6]. Calculations [7,8] have shown that it is dominated by second order 2-photon exchange and results in emission of a few neutrons with small (few MeV) kinetic energy in the nucleus rest frame. This paper deals with dissociation of Au ions of 65 GeV/nucleon, so these neutrons have small angular and energy spread with respect to the beam.

Experimentally, we measure the multiplicity of emitted neutrons along each beam direction with Zero Degree Calorimeters(ZDC's)[10] and determine the relative topological cross-sections $Au + Au \rightarrow N^{Left}_{neutrons} + N^{Right}_{neutrons} + X + Y$, where neutron multiplicities are specified but we sum over all possible emission of protons and gamma rays, for example. Specific channels are calculated in Refs. [7]and [8] and we compare to these predictions.

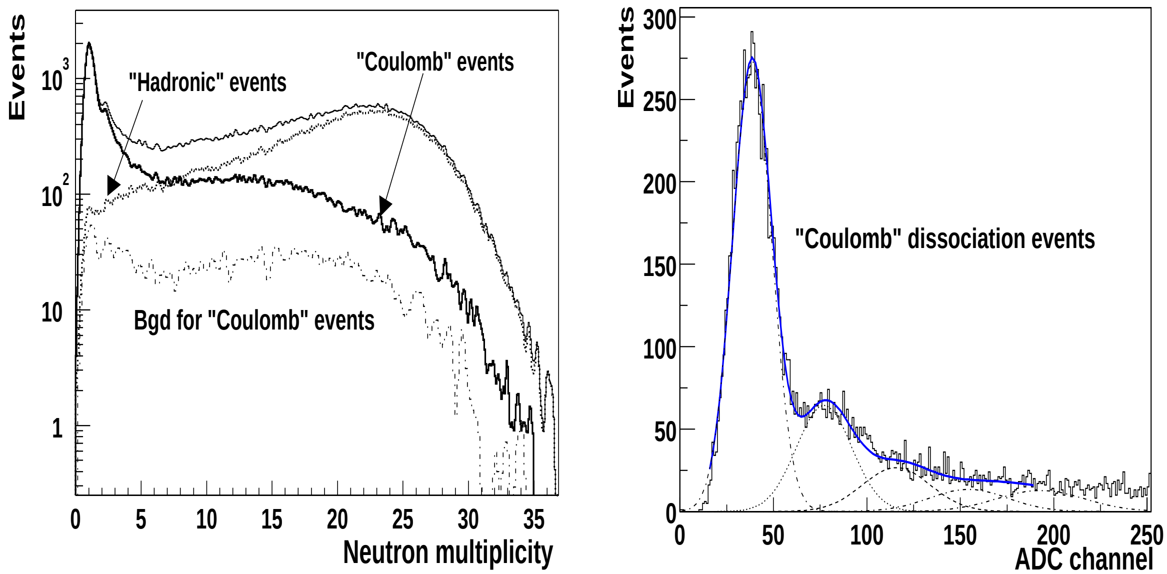

Figure 2: Single arm ZDC neutron multiplicity distribution(left figure). Left ZDC pulse height with "Coulomb" selection when Right ZDC pulse height is selected to be within the 1n peak(right figure).

In addition to measuring beam fragmentation neutrons, the RHIC experiments recorded hits in beam-beam counters, which indicated particle production in the central region, hence a nuclear collision. The geometrical cross-section for nuclear collisions (ie hadronic interactions) is derived on the basis of the Glauber model[7]. Using the determination of the geometrical cross-section previously reported by PHENIX [9] one may derive absolute cross-sections based on cross-section ratios presented herein to an accuracy of $\leq 5\%$.

3 Detector

The ZDC's are a common triggering device used in all of the experiments. In addition, PHENIX used a set of Beam-Beam Counters(BBC's)[9] on which we base the following discussion.

The ZDC's are small transverse-area hadron calorimeters which measure the energy of unbound neutrons in small forward cones around each beam ($|\theta| < 2$ mrad). The layout of the ZDC's is shown in Fig. 1 and further details can be found in Ref.[10]. The ZDC interaction trigger required a coincidence between ZDC's on either side of the interaction region (referred to as ZDC left, right) where a hardware threshold equivalent to 12 GeV was applied to the signal. The ZDC energy scale was determined from the one neutron and two neutron peaks which are clearly seen in Fig. 2. The energy resolution for 65 GeV neutrons was approximately 21% consistent with earlier test beam results[10].

The PHENIX BBC's are arrays of quartz Cerenkov detectors which measure relativistic charged particles produced in cones around each beam ($3.05 < |\eta| < 3.85$, with 2π azimuthal coverage). There are 64 photomultiplier (PMT) channels in each BBC arm. A BBC coincidence required more than 1 hit above a preset threshold ($n_{BBC} > 1$) in each arm. ZDC trigger events were selected if the event vertex was at $|z| \leq 20$ cm. A total of 160,601 ZDC trigger events satisfied these requirements.

The BBC coincidence was used in the present analysis to tag hadronic collisions for those events which trigger the ZDC's. In addition, PHENIX recorded several million events triggered with the BBC coincidence alone. These events were used to estimate the ZDC trigger efficiency for hadronic collisions.

For the purposes of this paper we identify 2 classes of events according to the number of hit BBC PMT's.

- Inelastic "Hadronic" events for which $n_{BBC} > 1$ in each arm.
- Peripheral, "Coulomb" events for which $n_{BBC} \leq 1$ in at least one arm.

4 Results

The fraction of events which satisfy the BBC requirement for Coulomb and hadronic collisions was derived from simulations of particle production in the 2 types of events. In Coulomb interactions, since most of the cross-section is due to equivalent photons with energy below particle production threshold, essentially all events satisfy the "Coulomb" event selection. In fact, the fraction of Coulomb interactions with a produced $\pi^{\pm}$ resulting in at least one BBC hit is found to be $\sim 3\%$[8] so vetoing on the coincidence introduces an inefficiency of $\leq 1\%$. On the other hand, $8 \pm 2\%$ of hadronic interactions[9] are estimated to fail the "Hadronic" BBC cut and these events represent a 14% contamination of the "Coulomb" sample.

The "Hadronic" BBC cut mis-identification is caused by peripheral hadronic events corresponding to a few elementary N-N collisions so low multiplicity BBC events were used to model the background in the "Coulomb" sample. Diffractive hadronic interactions are not treated in our Glauber model calculation and these are a potential background to our "Coulomb" sample. However this is a negligible correction since, for example, the high energy p-W diffraction dissociation cross-section[11] is 20 mb- which is a small fraction of the total p-W inelastic cross-section.

The ZDC multiplicity spectra are very different for the 2 classes of events as can be seen from Fig. 2; the "Coulomb" events tend to have low total neutron multiplicity whereas the fraction of "Hadronic" events with 1 or 2 neutrons is very small. The background (to the Coulomb) shape was calculated using low multiplicity tagged "Hadronic" events as described above and applied as a correction in what follows. As a check on consistency of this subtraction procedure, an un-normalized Coulomb ZDC multiplicity spectrum was obtained by measuring the left ZDC distribution with a 1 neutron cut on the multiplicity in the right one.This cut strongly suppresses nuclear collisions. This shape was then renormalized and subtracted from the raw "Coulomb" distribution. The background shape so obtained is identical within errors to that shown in Fig. 2.

The ZDC trigger efficiency correction was obtained from the geometrical acceptance for neutrons in the ZDC. Angular distributions and spectra of neutrons from low energy photoproduction experiments were used to compute the angular spread of Coulomb Dissociation neutrons about the beam direction[12,13]. The maximum p_t was 120 MeV so the maximum opening angle was less than 2 mrad. In the photoproduction experiments, the average neutron multiplicity was found to increase with photon energy. Comparable spectra for high energy photoabsorption are not available (note that ~20% of the MCD cross section is due to equivalent photons with energy $\geq$ 2 GeV) however we can safely assume that the mean neutron multiplicity is larger than 1 based on the lower energy data. Therefore, no ZDC acceptance correction is applied to the measured Coulomb rates.

The ZDC acceptance correction for hadronic collisions was both calculated using the p_t spectrum characteristic of a Fermi distribution[14] and measured using the independent BBC trigger sample. The calculated geometrical acceptance per neutron in the ZDC detector is 75%. From this acceptance and the observed spectrum of "Hadronic" events in Fig. 2 one can estimate the losses due to the ZDC requirement.

To directly measure the ZDC trigger efficiency we scanned the BBC trigger events for interactions in which the ZDC trigger condition failed. The measured efficiency is $98 \pm 2\%$ and this correction is applied to the calculated hadronic rates.

σ_i (barns)	Theory [7]	Theory [8]	PHENIX
σ_{tot}	10.8 ± 0.5	10.89	N.A.
σ_{geom}	7.09	7.29	N.A.
$\frac{\sigma_{geom}}{\sigma_{tot}}$	0.67	0.669	0.661 ± 0.014
Coulomb			
$\frac{\sigma(1n,Xn)}{\sigma_{tot}}$	0.125	0.134	0.117 ± 0.004
$\frac{\sigma(1n,1n)}{\sigma_{1n,Xn}}$	0.329	0.45	0.345 ± 0.012
$\frac{\sigma(2n,Xn)}{\sigma_{1n,Xn}}$	–	0.30	0.345 ± 0.014

5 Cross Sections

In what follows, we derive the cross-sections for various topologies of Coulomb events expressed as a fraction of the total ZDC cross-section.

The BBC trigger detects $[92 \pm 2(syst)]\%$ of the nuclear interaction cross-section (ie σ_{geom}) of 7.2b with a background contamination of $[1 \pm 1(syst)]\%$ [9]. Table 1 presents our measured value of the ratio of σ_{geom} to the total ZDC cross section, which is in good agreement with the ratio calculated in both refs. [7] and [8]. The ratio of "Hadronic" to "Hadronic"+"Coulomb" , as defined above, is corrected for BBC efficiency.

We fit the measured ZDC energy spectra to neutron multiplicity distributions, taking into account the experimental resolution of the ZDC's. We constrained the fits such that $\sigma_E(2n) = \sqrt{2} \times \sigma_E(1n)$, etc. Fig. 2 shows the energy spectrum obtained in one ZDC (ZDC left) for the "Coulomb" event selection when the other ZDC pulse height is consistent with 1 neutron. The distribution is fit to a linear sum of expected 1 neutron + 2 neutron, etc. energy distributions.

The total number of events in Fig. 2, after background subtraction, corresponds to the cross-section for the (1n,Xn) topology in which one neutron is observed in the right beam direction. We report, in Table 1, the sum of 1 neutron in left and right topologies as (1n,Xn). The fraction of events in the 1 neutron peak measures directly the number of (1n,Xn) with the decay topology (1n,1n), ie with exactly 1 neutron in both ZDC left and right. Of course, any number of protons could also be emitted in the reaction but these are not detected. Photons which hit the ZDC's would also contribute to the total energy measured. Details on the photon response may be found in Ref. [10].

Similarly the fits to specific neutron multiplicities in the ZDC's such as (2n,1n) are derived from simultaneous fits to ZDC left cut on ZDC right pulse height. The errors indicated include both statistical and systematic errors in the fit procedure. The dominant systematic error comes from sensitivity to the fitted lineshape. The dependence of the lineshape on the neutron multiplicity(ie that it grows as $\sqrt{N_{neutron}}$) is justifiable from first principles. However the fitted areas can vary significantly if this constraint on the relative peak widths is removed and this variation is used to derive the systematic errors quoted in Table 1.

6 Correlations

For Coulomb events each nucleus interacts independently with the field of the other and therefore one would expect no correlations between fragments from the left and right going nuclei. However for nuclear collisions both nuclei have the same number of "wounded nucleons" and therefore the left and right spectra should be correlated.

$$A(E_{Left}, E_{Right}) \equiv \frac{E_{Left} - E_{Right}}{E_{Left} + E_{Right}} \tag{2}$$

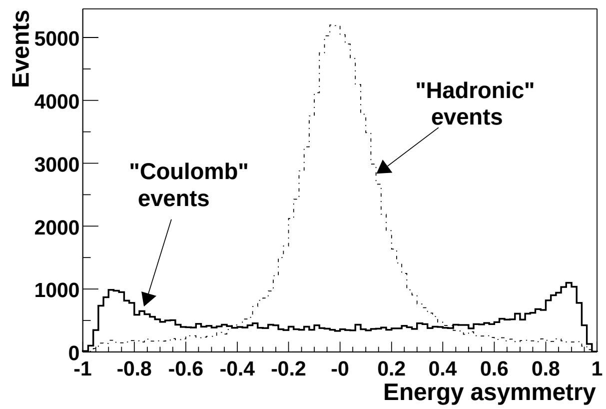

Figure 3: ZDC asymmetry distributions for Coulomb and nuclear events.

where E_{Left} and E_{Right} are the total ZDC energy signal in the Left and Right ZDC's respectively. For the Coulomb distribution in Fig. 3 we require > 1.5 neutrons energy equivalent in at least 1 of the ZDC's. This suppresses the (1n,1n) events which heavily skew the correlation function. The Coulomb distribution is also corrected for hadronic background.

7 Acknowledgments

I acknowledge my colleagues on the ZDC project and on PHENIX- particularly A.Denisov and M.Chiu with whom this analysis was performed. We thank the staff of the RHIC project, of the Collider-Accelerator. I thank Tony Baltz and Igor Pshenichnov for numerous useful discussions. This work was supported by the US Dept. of Energy.

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