**Correlated forward-backward Coulomb dissociation and
luminosity monitoring at heavy ion colliders**

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Abstract

We present an expression for the rate of correlated Coulomb dissociation of both colliding nuclei at a heavy-ion collider. For the case of Au + Au at RHIC, the cross section for mutual correlated dissociation is about 3 barns. This process should be cleanly measured with very forward (zero degree) calorimeters proposed for RHIC. We also discuss prospects for luminosity monitoring using this process.

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I. INTRODUCTION

The heavy ion collider experiments now being built for RHIC and the LHC will require, for their physics programs, luminosity monitoring devices. These monitors record a relatively well understood process simultaneously with the measurements of primary interest thereby making it possible to normalize relative to the monitor cross section.

For example, at e^+e^- and e - p colliders the luminosity monitoring device is a pair of calorimeters placed close to the beam direction which measure the energy and angle of outgoing particles from Bhabha scattering and Bethe-Heitler bremsstrahlung (e - $p \rightarrow e$ - p - γ) respectively.

At hadron colliders (ie $\bar{p}$ p) a luminosity monitor based on an arbitrary fraction of

the inelastic hadronic cross section has been used. Under special running conditions it has also been possible to measure directly elastic pp or $\bar{p}p$ scattering with momentum transfers small enough so that the Coulomb contribution is dominant ($|t| \sim .001 GeV^2/c^2$). This process can then be used to calibrate the monitor [3]. Another calibration procedure which has been used is the so-called “Luminosity independent method” for determining the total cross-section [6]. Since, at high energies the hadronic scattering amplitude is almost purely imaginary, an extrapolation of the differential elastic scattering rate to $|t|=0.0$ can, through the optical theorem, provide a measure of the total hadronic cross section. The alternate way of measuring the total cross section— summing up the scattering rate in all channels— depends on a different power of the luminosity (linear instead of square root) so the luminosity calibration is obtained as a by-product.

In the case of heavy ion collisions, elastic scattering is essentially unmeasurable because of the small scattering angles involved but there are a number of large cross section QED processes which could be exploited for luminosity monitoring.

In this report we present calculated cross sections for mutual correlated Coulomb dissociation at RHIC and LHC. We argue that this reaction, because it yields correlated neutrons in each beam direction with small p_T , is suitable for luminosity monitoring at ion colliders.

The layout of RHIC and LHC also makes it possible to detect neutrons close to 0° from the incident beam direction. There is already interest in other measurements that could be performed with a zero degree neutron calorimeter.

II. LUMINOSITY MEASUREMENT REQUIREMENTS

The experimental program determines the requirements for luminosity precision at RHIC. The current goal for is to achieve an accuracy of 5 – 10% on the luminosity measurement for any given experiment but more stringent requirements could appear as the program evolves.

The required specification for luminosity precision is often stated in reference to measurements with different beam energies or species. This is particularly true in the measurement of

departures from extrapolated pp behavior. There is apparently no alternative to measuring independently normalized production cross sections.

Another goal which is often stated for RHIC experiments is consistency in luminosity scale among different experiments—which would simplify comparison of results. This argues for the installation of identical luminosity measuring instruments that are independent of the rest of the experimental layout. This approach also has an enormous advantage in accelerator commissioning since the same trouble shooting tools can be used to tune each intersection region.

Finally, it should be recognized that instantaneous luminosity is also calculable from accelerator parameters ($I_{beam}, \sigma_x, \sigma_y$..) so long as beams are steered to give maximum overlap at the collision point. The Van der Meer method was employed at the first high energy light ion collider (the ISR) and should yield better than 10% precision at RHIC.

The purpose of the luminosity measurement using a standard physics cross section is to provide a real time monitor and to supply a cross check of the machine based determination. Since this exercise has been carried out many times for pp($\bar{p}$) colliders it is of interest to find a counterpart for the highest mass ion species.

A natural set of candidates is the virtual photo-nuclear processes since their cross sections grow rapidly with Atomic Number (approximately at least as fast as Z^4).

III. CANDIDATE PROCESSES FOR LUMINOSITY MONITORING

A number of processes may be considered for luminosity monitoring which all fail one of the following criteria:

- large cross section
- well understood acceptance for final state
- immunity from various possible backgrounds

Some examples, which illustrate this point follow.

A. Electron Pair Production Mediated by two Photon Exchange

The electron pair production cross section [8] is very large when running with Au beams ($\sigma \simeq 35$ kb) and this is a simple final state. However, because of the very steep q^2 dependence of the spectrum, the acceptance is difficult to calculate and may be very sensitive to details of the layout of the experiment— particularly magnetic fields. For example, in the STAR experiment most electrons are trapped by the detector's axial magnetic field before reaching the tracker. Because only the tail of a steeply falling spectrum is observed, the energy scale calibration also becomes part of the acceptance problem.

B. Coulomb Dissociation with Neutron Emission

This is also a large cross section with Au beam running ($\sigma = 95$ b [1] [2]) and it also gives rise to a simple final state— one or more neutrons which are emitted within a few mrad. of one of the beam directions. A calorimeter can be used to detect them and measure the number of neutrons by just dividing the total observed energy by the projectile energy per nucleon.

This process lacks a constraint on the point of production. Neutrons accompanying the outgoing beam could be produced by any number of “single-beam” processes, like beam-gas and beam- wall interactions. For this reason we reject this monitor in favor of a coincidence measurement.

C. Nuclear Inelastic Cross Section

Some sort of “minimum-bias” trigger will likely be in place for all experiments— generated by a coincidence of scintillator or Cerenkov hodoscopes on either side of the interaction region. This trigger will, by default, serve as the luminosity monitor for the different experiments. The acceptance of these hodoscopes is probably sensitive to other details of the experiment and not simply estimated from first principles.

Typically the PHENIX “Beam Beam Counter” system at RHIC covers $3.1 \leq \eta \leq 4.0$ and a 2 arm coincidence is sensitive to $\geq 90\%$ of the nuclear inelastic cross section in Au-Au collisions.

IV. CORRELATED FORWARD-BACKWARD COULOMB DISSOCIATION AT RHIC

The Coulomb dissociation of a single beam nucleus at RHIC has already been considered in some detail. [1] [2] The cross section for heavy-ion dissociation may be accurately expressed in terms of (generally experimentally known) photo-dissociation cross sections of the same nucleus over an appropriate energy range of photon energies. This is the so-called Weizsacker-Williams expression

$$\sigma_{dis} = \frac{2\alpha Z_p^2}{\pi\gamma^2} \int d\omega \omega \sigma_{ph}(\omega) \int_{b_0}^{\infty} b db K_1^2\left(\frac{b\omega}{\gamma}\right). \quad (1)$$

We may define a probability of dissociation, $P(b)$ as a function of impact parameter b

$$\sigma_{dis} = 2\pi \int_{b_0}^{\infty} P(b) b db. \quad (2)$$

Then inverting the order of integration in Eq. (1) we have

$$P(b) = \frac{\alpha Z_p^2}{\pi^2 \gamma^2} \int d\omega \omega \sigma_{ph}(\omega) K_1^2\left(\frac{b\omega}{\gamma}\right). \quad (3)$$

There is a problem with the analysis so far presented in that, as we will discover, this first order expression for $P(b)$ approaches unity near the grazing impact parameter for colliding heavy nuclei such as Au + Au. We will correct the expression to maintain unitarity later, but for the present we will continue with the first order analysis. The correlated dissociation cross section $\sigma_{cd}^{(1)}$ (here the (1) superscript indicates that this is a first order expression) requires both beam nuclei to be dissociated in an event. For identical colliding nuclei we have

$$\sigma_{cd}^{(1)} = 2\pi \int_{b_0}^{\infty} [P(b)]^2 b db, \quad (4)$$

or

$$\sigma_{cd}^{(1)} = \frac{2\alpha^2 Z^4}{\pi^3 \gamma^4} \int_{b_0}^{\infty} b db \left[\int d\omega \omega \sigma_{ph}(\omega) K_1^2\left(\frac{b\omega}{\gamma}\right) \right]^2. \quad (5)$$

The integral over ω and b can, of course, be evaluated numerically, and we will do so to obtain the numerical results we present below. However, it turns out that we can get a very accurate result analytically using the following scheme, which we will pursue for the present to elucidate the energy and impact parameter dependence of the mutual Coulomb dissociation. We evaluate the integral over ω in two pieces: above a certain value ω_m (say 18 GeV) $\sigma_{ph}^{(1)}$ is to a rough approximation a constant (which we call σ_c) thus simplifying its contribution as we show below; below ω_m we make the following approximation:

$$K_1^2\left(\frac{b\omega}{\gamma}\right) = \left(\frac{\gamma}{b\omega}\right)^2 \quad (6)$$

which is essentially exact (error of a part in a million) in the region of ω of the greatest contribution (the giant dipole resonance at about 14 MeV). Eq. (6) remains an excellent approximation up to 2 GeV, and introduces an error on the order of a few percent in the contribution between 2 and 18 GeV. We then have

$$\sigma_{cd}^{(1)} = \frac{2\alpha^2 Z^4}{\pi^3 \gamma^4} \int_{b_0}^{\infty} b db \left[\int_{\omega_0}^{\omega_m} d\omega \omega \sigma_{ph}(\omega) \left(\frac{\gamma}{b\omega}\right)^2 + \sigma_c \int_{\omega_m}^{\infty} d\omega \omega K_1^2\left(\frac{b\omega}{\gamma}\right) \right]^2. \quad (7)$$

But in the higher ω region we make an error of less than a percent with the approximation

$$\int_{\omega_m}^{\infty} d\omega \omega K_1^2\left(\frac{b\omega}{\gamma}\right) = (\gamma^2/b^2) \ln\left(\frac{.681\gamma}{b\omega_m}\right). \quad (8)$$

We may now integrate over b to obtain

$$\sigma_{cd}^{(1)} = \frac{\alpha^2 Z^4}{\pi^3 b_0^2} \left\{ \left[\int_{\omega_0}^{\omega_m} \frac{d\omega \sigma_{ph}(\omega)}{\omega} + \sigma_c \ln\left(\frac{.4131\gamma}{b_0 \omega_m}\right) \right]^2 + \frac{\sigma_c^2}{4} \right\} \quad (9)$$

It is clear that the evaluated cross section has a $1/b_0^2$ dependence, where b_0 is the minimum impact parameter for which events are purely Coulomb, with no density overlap and no hadronic interactions.

At this point let us obtain an expression for the cross section that preserves unitarity in $P(b)$. If we assume independence of the various modes of dissociation, then the probability of

at least one dissociation excitation of the nucleus is given by the usual Poisson distribution. Thus in our previous expression Eq.(4) we replace $[P(b)]^2$ with $[1 - e^{-P(b)}]^2$. We then evaluate the cross sections numerically on a computer.

Let us consider the standard design case of 100 GeV + 100 GeV Au + Au at RHIC. Seen in the frame of the nucleus being dissociated, the equivalent γ of the other ion providing the equivalent photons is 23,000. The experimental photo-dissociation cross section $\sigma_{ph}(\omega)$ that we utilized is shown in Fig.(1), which we have taken from Ref. [2].

In Table I we present calculated first order and unitarity corrected mutual Coulomb dissociation cross sections for two values of b_0 , 15 fermi and 17.3 fermi, corresponding to r_0 values of 1.29 and 1.49 respectively when one expresses b_0 in term of $2 \times r_0 A^{1/3}$. Cross sections are tabulated as a function of a cutoff in ω , which should correspond in some fashion to an experimental acceptance. For comparison, the corresponding cross sections for 2.76 TeV + 2.76 TeV Pb + Pb collisions at LHC are shown in Table II.

V. EXPERIMENTAL CONSIDERATIONS

Mutual dissociation could be measured with coincident detection of neutrons within a small angle of the incident beam direction. Neutrons which are emitted from the nucleus with kinetic energies of order 10 MeV will be contained within a forward cone of opening angle less than 1 milliradian.

Measurements have been reported on the kinetic energy distributions from Heavy Ion single dissociation [4]. The kinetic energy of neutrons from both single emission (1n,1p) and multiple emission (2p) were found to be less than 10 MeV.

A. Forward p_t Acceptance.

Both the RHIC and LHC accelerator designs can accomodate so-called zero degree calorimeters for neutron detection [5] [7]. In addition to energy measurement these detectors could provide precise time of flight information to aid in eliminating machine backgrounds.

Transverse dimensions of possible detectors are limited by the distance between beam orbits in the regions where access for detector placement is possible.

In the case of RHIC, running at a nominal momentum of 100GeV/c/u, and a detector size of ± 6 cm. @ 20m from the interaction point

$$\begin{aligned} p_t^{max} &= \frac{0.06}{20} \times 100 \text{GeV}/c \\ &= 300 \text{MeV}/c \end{aligned} \tag{10}$$

Therefore impacts from dissociation products should essentially always be contained.

At the LHC, with a nominal momentum of 2,760 GeV/c/u and a detector size of ± 4 cm @ 92 m from the interaction point

$$\begin{aligned} p_t^{max} &= \frac{0.04}{92} \times 2,760 \text{GeV}/c \\ &= 1,200 \text{MeV}/c. \end{aligned} \tag{11}$$

Thus in both cases there is no acceptance limitation- simply an instrumentation problem of measuring hadronic showers in such a small space.

B. Semi-inclusive Cross section

We note that photons contributing to the mutual dissociation process calculated here span a very wide range of energies. Although the nuclear final states will look very different above meson production threshold, we take the probability for emitting at least 1 neutron (with $T \sim 10$ MeV) to be a constant fraction of the total photonuclear cross section over the full energy range. This assumption implies some uncertainty since we know of no direct measurement of fragment Energy distributions in ~ 10 GeV photonuclear interactions. However measurements of “spectator nucleon” P_t distributions [4] in nuclear interactions at AGS energies show that some neutron fragments will likely impact in the zero degree calorimeter region.

Similarly the cross section dependence on impact parameter cutoff, b_0 , leads to an uncertainty in the dissociation cross section which also relates to possible detector bias. For

example, one might be tempted to reject events where multiple particle production occurs in the central region. At impact parameters corresponding to

$$b_0 = 2.0 \times A^{\frac{1}{3}} \times (1.5 fm.) \quad (12)$$

or less we expect to see the onset of central particle production due to strong interactions.

A detailed study of particle production vs impact parameter should decide whether the fraction of the mutual dissociation cross section in which no central particle production occurs is more reliably calculable than the full cross section presented here. In this paper we treat the fully inclusive cross section corresponding to small angle leading neutron emission in each beam direction but without additional bias.

C. Background from Uncorrelated Dissociation

A potential source of background which cannot be distinguished from the process of interest is the accidental coincidence of single dissociation events in each beam. Since the beams have a bunch structure at both accelerators this accidental rate can be simply calculated given the bunch frequency and the single dissociation cross section.

Let us consider the case of RHIC at the design luminosity of $2 \times 10^{26} cm^{-2} \cdot s^{-1}$ and the Day-1 bunch frequency of 4.8 Mhz. Then

$$\begin{aligned} R_{sd} &= L \cdot \sigma = 0.92 \times 10^{-22} \times 2. \times 10^{26} \\ &= 1.8 \times 10^4 \end{aligned} \quad (13)$$

is the rate of single dissociation events.

$$R_{crossing} = 4.8 \times 10^6 \quad (14)$$

is the rate of bunch crossings. A single dissociation event has a probability of $50\% \times \frac{R_{sd}}{R_{crossing}}$ of overlapping another single dissociation event of the "other" beam. Since this is identical to the mutual correlated dissociation topology we can define

$$\sigma_{acc} = 0.19 \times 10^{-2} \sigma_{sd} = 0.17 \text{ barns} \quad (15)$$

Clearly this effective cross section grows linearly with luminosity so long as the bunch frequency remains the same. The luminosity dependence could be used as a tool to evaluate this small background.

VI. CONCLUSION

The mutual correlated Coulomb dissociation process of heavy ion beams at RHIC and the LHC has a large cross section, comparable to the total hadronic cross section. Because of its clean topology and large cross section, this process can be cleanly measured at RHIC and the LHC. The planned machine design for RHIC and LHC also permits the installation of relatively simple detectors which would have essentially 100 % acceptance for this process.

It seems to us that these criteria make it suitable for luminosity monitoring in Heavy Ion running with the normal beams (Au and Pb respectively) intended for RHIC and the LHC.

The luminosity monitor we have in mind based on this process consists of recording events in which one Beam Energy nucleon (100 GeV at RHIC) is emitted at within 1-2 milliradians in each of the beam directions. The cross section for this process at RHIC is computed to be about 3 barns. Nuclear interactions of the ion beams can also give rise to coincident forward neutrons. Since the nuclear interaction cross section is approximately 6 barns this gives rise to a potential background. We would propose a very rudimentary veto of nuclear interaction events requiring a small total multiplicity.

Nevertheless, as discussed above, there are some uncertainties in the borderline between the 2 classes of events. This uncertainty in the mutual dissociation cross section is estimated to be approximately 10% when expressed as an impact parameter and photon energy cutoff. This is illustrated in Table 1.

Since the cross section varies as Z^4 , this luminosity monitor would, however, lose its usefulness for special runs with "light" ions such as Silicon and Sulfur. For light ion runs the

experiments will have to complement the Van der Meer measurement of luminosity with a “minimum bias” based monitor based on the nuclear interaction rate.

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FIGURES

FIG. 1. Photonuclear dissociation cross sections utilized for the Au + Au Coulomb dissociation calculations.

TABLES

TABLE I. First order σ_{cd}^1 and unitarity corrected σ_{cd} (in barns) for Au + Au at RHIC as a function of the cutoff photon energy ω_{max} (in MeV). Calculations are presented for two values of the lower impact parameter cutoff (see text).

ω_{max}	σ_{cd}^1		σ_{cd}	
	$b_0 = 15$	$b_0 = 17.32$	$b_0 = 15$	$b_0 = 17.32$
25	1.65	1.23	1.31	1.04
103	1.99	1.49	1.55	1.24
440	3.10	2.32	2.29	1.84
2000	4.21	3.16	2.98	2.42
17840	5.12	3.84	3.50	2.86
∞	5.91	4.39	3.90	3.19

TABLE II. As in Table I, but for Pb + Pb at LHC.

ω_{max}	σ_{cd}^1		σ_{cd}	
	$b_0 = 15$	$b_0 = 17.32$	$b_0 = 15$	$b_0 = 17.32$
25	2.21	1.66	1.71	1.36
103	2.66	2.00	2.01	1.61
440	4.12	3.09	2.92	2.37
2000	5.58	4.19	3.76	3.09
17840	6.79	5.09	4.42	3.65
∞	12.75	9.45	7.15	6.02

Photonuclear Absorption Cross Section

Au Target

Fig 1