Two Photon Physics at RHIC

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ABSTRACT

Because the two photon cross section is proportional to Z^4, heavy ion colliders offer an unmatched luminosity. However, because nuclei have finite sizes, the photon spectrum is gradually cut off by a nuclear form factor. For RHIC, this cutoff occurs at a few GeV; below this energy, RHIC will have the highest $\gamma\gamma$ luminosity in the world when it turns on. In addition to the high rates, because $Z\alpha \sim 0.6$, the nuclear environment provides a window to strong field QED and new phenomena like multiple pair production. To study $\gamma\gamma$ physics, regions where the nuclei interact hadronically must be avoided; this leads to roughly a factor of two loss in usable luminosity. The rates expected by the Solenoidal Tracker at RHIC (STAR) collaboration will be given. Backgrounds will be discussed, along with several rejection techniques.

1. Introduction

Two photon physics at heavy ion colliders offers some unique features. Because the cross section is proportional to Z^4, heavy ion colliders can produce unparalleled $\gamma\gamma$ luminosity. However, because the nuclei have finite sizes, the photon spectrum is cut off by a nuclear form factor. In addition, when the nuclei physically collide, they can produce thousands of particles through the strong interaction; in these collisions any $\gamma\gamma$ collisions will be obscured. These two factors reduce $\gamma\gamma$ luminosity at $\gamma\gamma$ energies above 2γ times the nuclear size, or about 6 GeV at RHIC.

RHIC is a 100 GeV per nucleon heavy ion collider now being built at the Brookhaven National Laboratory. Initial operation is scheduled for mid-1999. It will accelerate nuclei from protons to gold at the luminosities given in Table 1.[1] The luminosity for proton-nucleus collisions is roughly the geometric mean of the p+p and A+A luminosities.

2. Special Features of Heavy Ion collisions

There are a few important differences between heavy ion produced $\gamma\gamma$ interactions and $\gamma\gamma$ interactions produced in e^+e^- collisions: The particle charge Z is much larger and the nuclei have a significant size, $R(\text{fm}) \sim 1.2A^{1/3}$. In addition, since the nuclei

Nucleus	Z	E/A GeV/N	Luminosity (cm^{-2} sec^{-1})	$\gamma\gamma$ Luminosity (cm^{-2} sec^{-1})
Au+Au	79	100	2.0×10^{26}	7.8×10^{33}
I+I	53	104	2.7×10^{27}	2.1×10^{34}
Cu+Cu	29	115	9.5×10^{27}	6.7×10^{33}
Si+Si	14	125	4.4×10^{28}	1.7×10^{33}
O+O	8	125	9.8×10^{28}	4.0×10^{32}
p+p	1	250	1.4×10^{31}	1.4×10^{31}
p+Au	1,79	100	$\sim 1 \times 10^{29}$	6×10^{32}

Table 1: The expected beam energies, luminosities and $\gamma\gamma$ luminosities for various ion species at Brookhaven. The $\gamma\gamma$ luminosity is the nuclear luminosity multiplied by Z^4, the cross section enhancement.

only lose a small fraction of their energy, there is no tagging in nuclear collisions.

2.1. Nuclear Charge

The obvious implication of the large Z is a large interaction rate, proportional to Z^4. For gold ions, this factor is 4×10^7. Despite the relatively low nuclear luminosity, RHIC will have the highest $\gamma\gamma$ luminosity in the world up to a few GeV.

The large nuclear charge also has some subtler implications. For gold, $Z\alpha \sim 0.6$. This makes it easy to add extra photons to any Feynman diagram, and one can wonder if perturbation theory holds. Geometry gives a partial answer. If the photon wavelength is smaller than the nuclear size (30 MeV/c for gold), then the photons are effectively localized in different positions around the nucleus, and so are unlikely to physically overlap, so perturbation theory should still hold.

At low momenta (less than the inverse nuclear size), the situation is more complicated. Some authors have argued that perturbation theory does break down, and nonperturbative calculations are needed. A number of non-perturbative calculations have been done, sometimes finding answers many orders of magnitude larger than the perturbative results. The nuclei are placed on a grid, and the time dependent Dirac equation is solved at each time step.[2] Unfortunately, these calculations require much computer time, and, as the authors have admitted, do not yet converge. Other authors have pointed out that the calculations are not yet gauge invariant, and furthermore are based on inconsistent or overlapping basis states.[3]

As an experimentalist, the situation is clear: good data is needed. Results from CERN WA-90 indicate that the e^+e^- production rate is slightly lower than Monte Carlo predictions.[4] However, more data is needed to draw firm conclusions.

Another consequence of the large $Z\alpha$ is that the cross section for e^+e^- pair production violates unitarity; at small impact parameters b, $d\sigma/db > 2\pi b db$ and the calculated cross section is larger than the available geometric area. This has been discussed by a number of authors; they find that multiple pairs are produced.[5]

Another interesting effect is pair production with the negative particle bound to the nucleus. This may be calculated perturbatively, using the bound electron wave function in the final state.[6] Nuclei that capture an electron are shortly lost to the beam; this will limit the beam lifetime at RHIC.

Capture can only occur if the negative particle can be produced nearby in phase space to the nucleus. To conserve energy and momentum, this can only occur if the particle mass is small compared to whatever photon energy cutoff is assumed, in the nuclear frame. For the hard 30 MeV/c nuclear size cutoff, capture is only possible for electrons. Perturbative calculations show that capture is marginally possible for muons[7] and probably pions, but not likely for heavier particles.

2.2. Nuclear Size

The nuclear size introduces a cutoff in the photon energy spectrum. For the nucleus to contribute coherently to the photon intensity, the photon wavelength must be larger than the nuclear size. For gold, the nuclear radius R is about 7 fermi, equivalent to a cutoff of about 30 MeV/c. Transformed to the laboratory frame of reference, the cutoff becomes γR, or about 3 GeV/c for gold at RHIC. A hard cutoff at the nuclear size gives a photon spectrum $dN/d\omega = Z^2\alpha/\pi\omega\ln(\gamma\delta/\omega R)$ with $\delta = 1$.

A better estimate of the spectral cutoff may be obtained by approximating or measuring the nuclear charge distribution and Fourier transforming it. One calculation using a Gaussian distribution finds the same formula, but with $\delta \sim 1.7$.[8] Other analyses have found somewhat different forms with softer cutoffs.[9]

This cutoff is not critical because it is overshadowed by another requirement. When two nuclei collide with an impact parameter b$< 2R$, then the nuclear interactions produce tens to thousands of particles, obscuring any simultaneous $\gamma\gamma$ interactions. So, most calculations of useful $\gamma\gamma$ luminosity exclude the region of phase space where the nuclei collide. They also avoid the regions inside the nuclei, and hence the need for an explicit form factor.

This approach can be implemented by integrating the product of $dN/d\omega(b)$ for the photons over all space and impact parameters. Figure 1a compares the result with and without the overlap region, following the formalism of Cahn and Jackson.[9] Avoiding the overlap region $b < 2R$ leads to roughly a factor of two loss of luminosity.

3. Backgrounds

One essential task for $\gamma\gamma$ research at a heavy ion collider is to remove the backgrounds due to grazing nuclear collisions. The background occurs when heavy nuclei

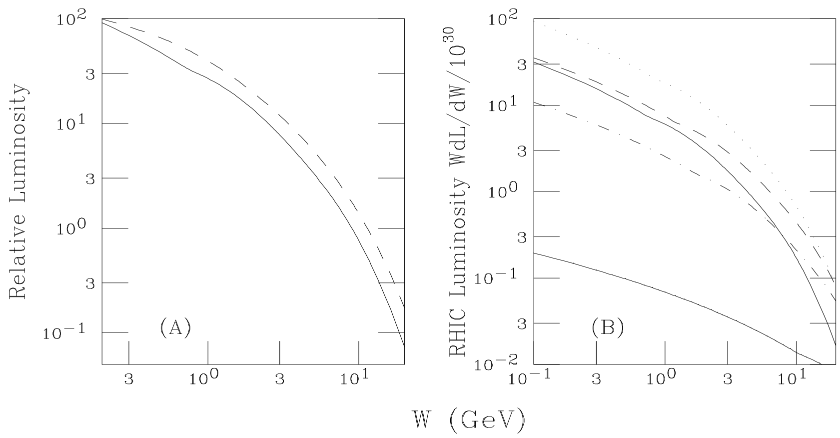

Figure 1: (A)The relative luminosity, including (dashed line) and excluding (solid line) the regions where the nuclei overlap. (B). The RHIC $\gamma\gamma$ luminosity, for gold (solid line), iodine (dots), copper (dashed line), silicon (dot-dash) and protons (bottom solid line). The luminosity curves for the lighter nuclei are considerably flatter, and the highest luminosity is obtained for iodine, not gold. This plot includes the varying nuclear E/A and luminosity attainable at RHIC.

graze each other, and one or more nucleons interact. The simplest model for this is gluon exchange; other relevant backgrounds are due to photon-gluon fusion and Pomeron exchange. Three main variables appear useful for separating $\gamma\gamma$ signal from nuclear backgrounds.

• Multiplicity. In 100 GeV NN collisions, the average multiplicities $N_{\rm ch} \sim 14.5$ and $N_\gamma \sim 14.5$ are much larger than the multiplicities in typical $\gamma\gamma$ final states.

• Perpendicular Momentum. The perpendicular momentum scale of a photon is the nuclear size $\sim$30 MeV/c for gold. In contrast, the perpendicular momentum scale for strong interactions is much larger, $\sim$ 150 MeV/c.

• Nuclear breakup. In a nuclear interaction the nucleus is likely to break up, emitting one or more nucleons. On the other hand, in a photon mediated collision, nuclei are likely to stay intact. Estimates of the breakup rates are discussed elsewhere.[10] Zero degree calorimeters surrounding the beampipe can detect this breakup.

A sample calculation can give us a rough idea of the background levels. The geometric cross section for a single nucleon- single nucleon mediated interaction in a gold-gold collision is about 3.5 mbarns. Using this cross section and using KNO scaling from ISR data to predict the multiplicity distributions, we expect that the cross section to produce four charged and two neutral pions is about 50μb, producing about 10^5 events/year. The FRITIOF Monte Carlo predicts a somewhat higher average multiplicity then KNO scaling for single interactions in Au-Au events, and should lead to lower background predictions. Cuts on $p_\perp$ will reduce this by a factor of 5-10. These can be followed by cuts on nuclear breakup and particle identification

Final State	Cuts	Rate
e^+e^-	$p_\perp > 150$ MeV/c	10s of Hz
$\mu\mu$	$p_\perp > 150$ MeV/c	10^5/year
$\tau\tau$		30,000/year
$\pi\pi$,KK,pp pairs	$p_\perp > 150$ MeV/c	$10^4 - 10^5$/year
f2(1270), A2(1320)		$> 10^6$/year
η_c,χ_{c2},η_c'		500,000, 90,000, 50,000/year
open charm		180,000/year
η_b		100/year

Table 2: The expected production rates for various final states at RHIC, for gold on gold running. The η_b rate is given for reference only; it is unlikely to be detected at RHIC. The $p_\perp$ cuts on pair production appear required for STAR triggering.

and mass constraints. Even with conservative estimates about the effectiveness of these cuts, these rates seem very manageable.

It is worth pointing out that photon gluon fusion events and Pomeron exchanges may offer additional physics opportunities.

4. The RHIC Program

The rates for some interesting $\gamma\gamma$ final states[11] are given in Table 2. Since the initial running will be gold on gold, those rates are given here. For lighter ions, such as iodine or copper the rates are up to three times higher, as shown in figure 1B.

RHIC will have four detectors. The Solenoidal Tracker at RHIC (STAR) is a large solid angle TPC tracking detector with electromagnetic calorimetry. PHENIX is optimized for electrons, muons and photons. BRAHMS is a small solid angle precision spectrometer, and PHOBOS is designed to measure charged and neutral multiplicities down to small $p_\perp$ over almost the full solid angle.

For most of these final states, a detector sensitive to charged and neutral particles is needed; STAR has been designed to measure the momenta and energies of charged and neutral final states over a large solid angle.[12]

4.1. STAR

Charged particles are tracked in a 5 kG solenoidal field by a TPC out to pseudorapidity $|\eta| < 2$. Around the TPC is a 100 psec TOF system, surrounded by a lead-scintillator electromagnetic calorimeter with resolution $\sigma(E)/\sqrt{E} \sim 0.16$. Zero degree calorimeters surround the beampipe and can detect neutrons or protons that break off of nuclei, down to zero perpendicular momentum.

STAR also has an extremely flexible trigger. It can be programmed to accept both very high (for central nuclear collisions) or very low (for $\gamma\gamma$ events) multiplicity events. After event readout, the level 3 tracking trigger could check the perpendicular momentum balance of the event. Detailed studies of the triggering requirements for $\gamma\gamma$ events are now in progress.

5. Conclusions

RHIC will offer many new opportunities for $\gamma\gamma$ physics. In addition to the unique opportunities to probe the limits of perturbation theory, RHIC will also offer unprecedented luminosity for $\gamma\gamma$ collisions up to about 6 GeV, allowing for high statistics studies of scalar meson production, charmonium and pair production.

The STAR detector appears well placed for much of this conventional $\gamma\gamma$ physics.

$\gamma\gamma$ physics with heavy nuclei is relatively new; there is much fertile ground to be covered, and much room for thought and innovation.

6. Acknowledgements

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