MEASUREMENT OF THE TOTAL CROSS SECTION OF GOLD-GOLD COLLISIONS AT $\sqrt{s_{NN}} = 200$ GeV*

W. Fischer†, A.J. Baltz, M. Blaskiewicz, D. Gassner, K.A. Drees, Y. Luo, M. Minty, P. Thieberger,
Brookhaven National Laboratory, Upton, NY 11973, USA;
I.A. Pshenichnov, Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

Abstract

Heavy ion collision cross sections totaling several hundred barns have been calculated previously for the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These total cross sections are more than one order of magnitude larger than the geometric ion-ion cross sections, primarily due to Bound-Free Pair Production (BFPP) and Electro-Magnetic Dissociation (EMD). Apart from a general interest in verifying the calculations experimentally, an accurate prediction of the losses created in the heavy ion collisions is of practical interest for RHIC and the LHC, where some collision products are lost in cryogenically cooled magnets. These losses have the potential to affect power and signal electronic devices and quench superconducing magnets. We have previously reported the total cross section measurement of U+U collisions at a center-of-mass energy of 192.8 GeV per nucleon-pair. Here we present the equivalent analysis for Au+Au collisions with the data available from a low-intensity store of RHIC Run in 2014.

INTRODUCTION

In a previous paper [1] we reported on the measurement of the total U+U cross section in RHIC collider operation when nearly all ions are lost due to burn-off. In this article we perform the same analysis for the total Au+Au cross section with a much smaller data set.

The large total cross sections of colliding heavy ion beams are primarily due to Bound-Free Pair Production (BFPP) and Electro-Magnetic Dissociation (EMD). We reproduce the summary of the calculated cross sections for the Relativistic Heavy Ion Collider (RHIC) [2, 3] and the Large Hadron Collider (LHC) [4, 5] in Table 1 [1].

Secondary beams from BFPP and EMD can limit the LHC heavy ion luminosity since they have a different charge-to-mass ratio than the primary beam and may be lost in cold magnets. Secondary beams generated in Au+Au collisions in RHIC are presently lost in the arcs, where the lattice function ratio $D_x/\sqrt{\beta_x}$ reaches a maximum. When large orbit bumps are installed in the arcs to protect the experiments from an abort kicker pre-fire, as was the case in 2016, the losses of the secondary beams are localized and have likely contributed to the shorting a quench protection diode.

Table 1: Calculated total cross sections for Au+Au and U+U collisions in RHIC, and Pb+Pb collisions in the LHC [1]. The total cross section is given by the sum of BFPP, single EMD, and nuclear cross sections. The mutual EMD cross section is given for reference only.

collider		RHIC	RHIC	LHC
species		Au+Au	U+U	Pb+Pb
$\sqrt{s_{NN}}$	GeV	200	192.8	5520
BFPP	b	117	329	272
single EMD	b	94.15	150.1	215
mutual EMD	b	*3.79*	*7.59*	*6.2*
nuclear	b	7.31	8.2	7.9
total	b	218.46	487.3	494.9

The measurement of the total cross section σ_{tot} is based on the observed beam loss rates and luminosities with the two RHIC experiments (STAR and PHENIX) when nearly all of the ions are lost through burn-off. With complete burn-off the beam loss rate is given by

$$\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = -\left[\mathcal{L}_6(t) + \mathcal{L}_8(t)\right]\sigma_{tot} \quad (1)$$

where N_B and N_Y are the Blue and Yellow beam total intensities, and $\mathcal{L}_6(t)$ and $\mathcal{L}_8(t)$ the instantaneous luminosities at interaction points IP6 (STAR) and IP8 (PHENIX) respectively.

The principal limitation of the measurement are non-luminous losses that are unaccounted for. In their presence the measurement only gives an upper bound for the total cross section σ_{tot}. We therefore limit the analysis of the total Au+Au cross section to a single low-intensity store.

In Ref. [1] we reported a measured total U+U cross section of $\sigma_{tot}^{meas} = (515 \pm 13^{stat} \pm 22^{sys})$ barn at $\sqrt{s_{NN}} = 192.8$ GeV, with a combined statistical and systematic error of 26 barn or 5.0%. The calculated value is $\sigma_{tot}^{calc} = 487.3$ barn (Table 1), smaller than the measured value by 28 barn or 5.4%.

CROSS SECTION MEASUREMENT

In Au+Au operation in 2014 (Table 2) the initial bunch intensity ($N_b = 1.60 \times 10^9$) was more than 5 times larger than the initial bunch intensity with U+U in 2012 ($N_b =$

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
† Wolfram.Fischer@bnl.gov

0.30×10^9, [1]). While this leads to an order of magnitude increase in the average luminosity it also substantially increases the non-luminous losses. This is due to the reduced cooling speed and the greater sensitivity to intensity dependent effects, among them the beam-beam interaction.

A clear sign of non-luminous losses are beam loss rates $\dot{N}_{B,Y}$ that are visibly different in the two RHIC beams, and loss rates that are not proportional to the total luminosity $\mathcal{L}_6 + \mathcal{L}_8$. Both of these features can be routinely observed in physics stores with full intensity. We therefore limit the determination of the total Au+Au cross section to a single low-intensity store that had been requested by the STAR experiment (fill 18196, Fig. 1). The initial bunch intensity for this fill ($N_b = 0.20 \times 10^9$, Table 2) is even smaller than the initial bunch intensity of the U+U stores in 2012.

Table 2: Main beam parameters typical during Au+Au operation, and for the selected store used in total cross section measurement. Values are given for the beginning of store ($\mathcal{L}_0$) and the time of maximum luminosity ($\mathcal{L}_{max}$.)

parameter	unit	operations at $\mathcal{L}_0$	operations at $\mathcal{L}_{max}$	fill 18196 at $\mathcal{L}_0$	fill 18196 at $\mathcal{L}_{max}$
beam energy E	GeV/nucleon	96.4		100.0	
number of bunches n	...	111		111	
bunches colliding at IP6 n_{c6}	...	102		102	
bunches colliding at IP8 n_{c8}	...	111		111	
bunch intensity N_b	10^9	1.6	1.35	0.20	0.18
beam current I_b	mA	176	148	28	25
rms emittance ε_{xy}	μm	2.5	1.35	1.94	0.60
luminosity $\mathcal{L}$/IP	10^{26} cm^{-2}s^{-1}	80	84	1.9	5.4
abs. beam loss rate $\dot{N}$	1000/s	4000	4000	93	233
rel. beam loss rate $\dot{N}/N$	%/h	8	10	1.5	4.2

Figure 2 shows the beam loss rates for the Blue and Yellow beams respectively as a function of the total luminosity $\mathcal{L}_6 + \mathcal{L}_8$ for fill 18196, and the result of the fitted σ_{tot} for both beams according to Eq. (1). The average of the 2 fit values is $\sigma_{tot}^{meas} = 215$ barn.

EXPERIMENTAL ERROR

Given the close beam parameters of the Au+Au fill 18196 to the beam parameters of U+U stores in 2012 we use the error analysis of the U+U collisions [1] with an update of the systematic luminosity error $\Delta\mathcal{L}^{sys}/\mathcal{L}$.

Statistical error. In the U+U analysis the variation of the σ_{tot} fit values was much larger than the statistical standard fit error of each individual fit. The statistical error was therefore determined as the standard deviation of the 28 fitted σ_{tot} values and stated at the 5σ confidence level [1].

With only 2 fit values for σ_{tot} in Au+Au we cannot determine a statistical standard deviation from the fit values. We will use the relative experimental standard devision determined in U+U collisions, 2.5%, and calculate the Au+Au statistical standard error (also at the 5σ confidence level) as $\Delta\sigma^{stat}/\sigma_{tot} = (5/\sqrt{2}) \times 2.5\% = 8.8\%$, or $\Delta\sigma^{stat} = 19$ barn.

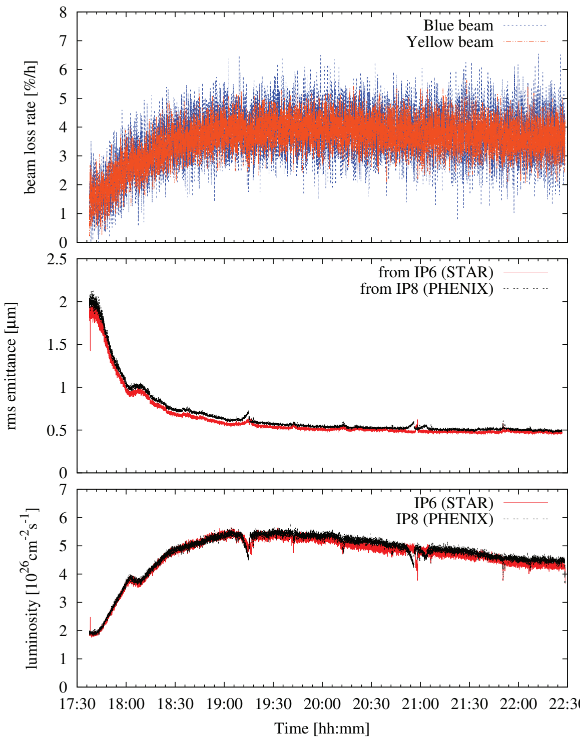

Figure 1: Au+Au store (fill 18196) with relative beam loss rates (a), normalized rms emittances calculated from luminosity and intensity (b), and luminosities at the STAR and PHENIX experiments (c). The reduction in the emittances and the corresponding increase in the luminosity are due to stochastic cooling during store.

Systematic error. From Eq. (1) the systematic error can be derived as

$$\frac{\Delta\sigma^{sys}}{\sigma_{tot}} = \frac{\Delta\dot{N}_{B,Y}^{sys}}{\dot{N}_{B,Y}} + \frac{\Delta\mathcal{L}_6^{sys} + \Delta\mathcal{L}_8^{sys}}{\mathcal{L}_6 + \mathcal{L}_8}. \quad (2)$$

The analysis of the relative error in the beam loss rate yields is the same result as for U+U, $\Delta\dot{N}_{B,Y}^{sys}/\dot{N}_{B,Y} = 0.4\%$. An analysis of the relative luminosity error yields $\Delta\mathcal{L}^{sys}/\mathcal{L} = 5.2\%$, and the total systematic error is $\Delta\sigma^{sys}/\sigma_{tot} = 5.6\%$.

SUMMARY

In a low-intensity Au+Au store at $\sqrt{s_{NN}} = 200$ GeV with 3D stochastic cooling nearly all beam losses are from burn-off and the total interaction cross section can be obtained from the observed beam loss rates as

$$\sigma_{tot}^{meas} = (215 \pm 5^{stat} \pm 12^{sys}) \text{ barn} \quad (3)$$

with a combined statistical and systematic measurement error of 13 barn or 6.0%. The principal limitation of the measurement method are non-luminous beam losses that are not accounted for. If these exist the measurement only delivers an upper limit for σ_{tot}^{meas}. The calculated total cross section of $\sigma_{tot}^{calc} = 218.5$ barn is larger than the measured one by 3.5 barn or 1.6%, a deviation within the combined experimental error.

ISBN 978-3-95450-147-2

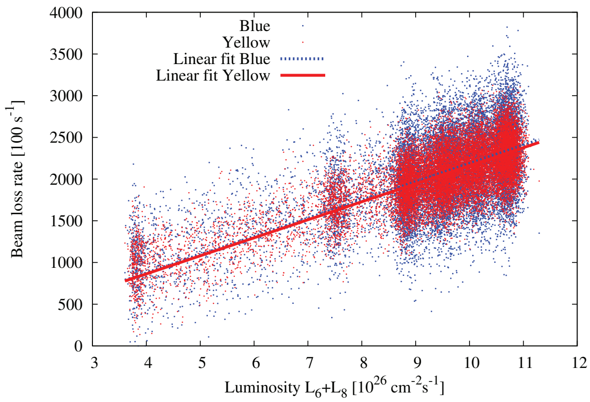

Figure 2: Blue and Yellow beam loss rates as a function of the total luminosity $\mathcal{L}_6 + \mathcal{L}_8$ for fill number 18196. The units for the luminosity and beam loss rates are chosen so that the linear fit coefficient is returned in units of barn. Fitted values case are $\sigma_{tot} = (216.02 \pm 0.31)$ barn for Blue, and $\sigma_{tot} = (213.25 \pm 0.21)$ barn for Yellow. The error is the statistical standard error.

ACKNOWLEDGMENTS

The authors are thankful for discussions and support to J. Bergoz, S. Binello, R. Bruce, W. Christie, T. Hayes, X. He, M. Mapes, K. Smith, and J. Jowett.

REFERENCES

[1] W. Fischer, A.J. Baltz, M. Blaskiewicz, D. Gassner, K. A. Drees, Y. Luo, M. Minty, P. Thieberger, M. Wilinski, and I.A. Pshenichnov, Phys. Rev. C 89, 014906 (2014).

[2] H. Gould, Lawrence Berkeley Laboratory Report No. LBL-18593 (1984).

[3] A.J. Baltz, M.-J. Rhoades-Brown, and J. Wesener, Phys. Rev. E **54**, 4233 (1996).

[4] S.R. Klein, Nucl. Instrum. Methods Phys. Res., Sect. A **459**, 51 (2001).

[5] J.M. Jowett, J.-B. Jeanneret, and K. Schindl, Proceedings of the Particle Accelerator Conference 2003, Portland, Oregon, pp. 1682-1684 (2003).