Higher order QED in high mass $e^+e^-$ pairs production at RHIC

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Lower order and higher order QED calculations have been carried out for the RHIC high mass $e^+e^-$ pairs observed by PHENIX with single ZDC triggers. The lowest order QED results for the experimental acceptance are about two standard deviations larger than the PHENIX data. Corresponding higher order QED calculations are within one standard deviation of the data.

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A recent publication of the PHENIX collaboration at RHIC has presented data on ultraperipheral Au + Au photoproduction of the $J/\psi$ and of continuum $e^+e^-$ pairs in the invariant mass range of 2.0 – 2.8 GeV/c$^2$. The present paper concerns itself not with the $J/\psi$ but with the continuum pairs. A previous measurement of $e^+e^-$ pairs at RHIC was carried out by the STAR collaboration in the somewhat lower invariant mass range 140 – 265 MeV/c$^2$, and it was subsequently argued that these data exhibited evidence for higher order QED effects. This paper presents results of a higher order QED calculation for the PHENIX data using the same methodology as the calculations previously published for the STAR data.

The PHENIX data was presented as a differential cross section with respect to the pair equivalent mass $m_{e^+e^-}$ and the pair rapidity $y_{\text{pair}}$, with the constraint of at least one neutron detected in one of the zero degree calorimeters (ZDC): $d^2\sigma/dm_{e^+e^-}dy_{\text{pair}}(e^+e^- + Xn, y_{\text{pair}} = 0)$. The differential cross section at $y_{\text{pair}} = 0$ was taken from the sample $|y_{\text{pair}}| < 0.35$ but with no constraint on pseudorapidity $\eta$ of individual electrons and positrons. However, since the events measured by PHENIX detector had both the electron and positron pseudorapidities within $|\eta| < 0.35$, the stated results without the individual $|\eta| < 0.35$ were necessarily constructed from a model calculation. The PHENIX publication states, “The fraction of events with $|y_{\text{pair}}| < 0.35$ and $2.0 < m_{e^+e^-} < 2.8$ GeV/c$^2$, where both electron and positron are within $|\eta| < 0.35$ is 1.10%. The corresponding numbers for $2.0 < m_{e^+e^-} < 2.3$ GeV/c$^2$ and $2.3 < m_{e^+e^-} < 2.8$ GeV/c$^2$ are 1.11% and 1.08%, respectively." Since we wanted to carry out calculations closest to what PHENIX actually measured, here we calculate the cross sections with the electron and positron constraints $|\eta| < 0.35$ and compared with the cross sections in the PHENIX publication multiplied by 0.011, etc. (see also Ref. 4).

Following the method of the higher order calculations previously used for the STAR data, the cross sections here are computed from the product of the pair production probability $P_{ee}(b)$, the probability at least one of the ions Coulomb dissociating $P_{1x}(b)$, and a survival factor $\exp[-P_{nn}(b)]$ to exclude events where hadronic interactions occur

$$\sigma = 2\pi \int P_{1x}(b)P_{ee}(b)\exp[-P_{nn}(b)]db. \quad (1)$$

Unlike the STAR Coulomb dissociation factor $P_{xx}(b)$, which corresponds to neutrons detected in both ZDCs,

$$P_{xx}(b) = [1 - \exp(-P_C(b))^2, \quad (2)$$

here the corresponding Coulomb dissociation factor $P_{1x}(b)$ is the unitarized probability that requires only that at least one of the colliding nuclei suffers Coulomb dissociation

$$P_{1x}(b) = [1 - \exp(-2P_C(b)). \quad (3)$$

$P_C(b)$ the non-unitarized probability of a single Coulomb excitation calculated in a phenomenological model for the ZDC neutrons derived from photodissociation data. The non-unitarized hadronic interaction probability $P_{nn}(b)$ is calculated in the usual Glauber manner

$$P_{nn}(b) = \sigma_{nn} \int dxdy T_A(x,y) T_A(x-b,y). \quad (4)$$

where $\sigma_{nn}$ is the total hadronic interaction cross section, 52 mb at RHIC, b is the impact paramete, and the nuclear thickness function $T_A(x',y)$ is the longitudinal integral of the nuclear density, $\rho(r)$

$$T_A(x',y) = \int dz \rho(x',y,z)dz. \quad (5)$$

The nuclear density profile $\rho(r = \sqrt{x^2 + y^2 + z^2})$ of heavy nuclei is well described with a Woods-Saxon distribution. We use parameters determined from electron scattering data (R=6.38 fm a=0.535 for Au).

The perturbative and higher order QED pair production probabilities $P_{ee}(b)$ were calculated using the methods previously described. In the $P_{ee}(b)$ calculations an analytical elastic form factor was employed

$$f(q) = \frac{3}{(qr)^3} \left[ \sin(qr) - qr \cos(qr) \right] \left[ \frac{1}{1 + a^2q^2} \right] \quad (6)$$

with a hard sphere radius $r = 6.5$ fm and Yukawa potential range $a = 0.7$ fm. This form very closely reproduces
TABLE I: RHIC: Au + Au, γ = 107, single ZDC triggered $e^+e^-$ pairs cross section ($\sigma/dm_{e^+e^-}$ $d\eta$/GeV) with PHENIX cuts (see text).

| $m_{e^+e^-}$ (GeV/c²) | Data | Starlight | Perturbative | Higher Order |
|----------------------|------|-----------|--------------|--------------|
| [1, 4]               | [9]  | QED [3, 7] | QED [3, 7]   |              |
| 2.0 – 2.8            | 0.95 ± 0.31 | 0.99 | 1.69 | 1.24 |
| 2.0 – 2.3            | 1.43 ± 0.61 | 1.53 | 2.60 | 1.90 |
| 2.3 – 2.8            | 0.65 ± 0.30 | 0.66 | 1.14 | 0.83 |

the Fourier transformation of the Au density with the Woods-Saxon parameters mentioned above[8].

Calculations in Ref.[1] performed with the computer program Starlight[9] differed from the present calculation only in the use of an equivalent photon probability $P_{ee}(b)$ in Eq. (1) instead of the QED probability $P_{ee}$[10]. The Coulomb dissociation probability $P_{ee}(b)$ and hardronic survival probabilities $\exp[-P_{nn}(b)]$ were treated as described above identically in both calculations. The equivalent photon probability $P_{ee}(b)$ uses the Weizsacker-Williams photon spectrum calculated for the heavy ions and the Breit-Wheeler cross section for $\sigma(\gamma + \gamma \rightarrow e^+ e^-)[3]$. In Starlight it is also required that photons originate only outside the nuclear radius $R$ of each of the ions, and in the PHENIX calculations, a hard sphere radius $R = 6.98\text{ fm}$ was used for this sharp cutoff.

Results are shown in Table I. The stated statistical and systematic errors in the data have been combined in quadrature. As indicated above, calculations are for the measured Au + Au reaction at $\gamma = 107$ for each of the Au nuclei. $e^+e^-$ pairs were accepted for $|\eta_{\text{pair}}| < 0.35$ with a ZDC trigger indicating simultaneous dissociation of at least one of the gold nuclei. Individual electrons and positrons were also accepted only for mid-rapidity $|\eta| < 0.35$. The calculated cross section is defined for a pair to literally fall within the cuts: $y_{\text{pair}}$, individual $e^+$ and $e^-$ $|\eta|$, and $m_{e^+e^-}$, but normalized to unit $y_{\text{pair}}$ and $m_{e^+e^-}$.

As was shown in the original PHENIX publication, the Starlight calculations are in very good agreement with the data. The present QED perturbative calculations are about two standard deviations higher than the data, while the higher order calculations are higher than the data but within one standard deviation for all three $m_{e^+e^-}$ ranges.

One might reasonably ask why the perturbative QED calculations are so much higher than the perturbative Weizsacker-Williams calculations. In the first place one has to recognize that Weizsacker-Williams calculations are an approximation to the more proper QED calculations, in particular neglecting the viruality of the intermediate photons. However there is another physics difference between the two calculations. In the QED calculation there is no sharp cutoff analogous to the cutoff at the hard sphere nuclear radii $R$ in the STAR equivalent photon calculation, but the form factor, Eq. (6) gives a smooth cutoff in both transverse and longitudinal photon momenta arising from the nuclear Woods-Saxon charge distribution. This smooth cutoff allows more high momentum photons contributing to the cross section than a sharp cutoff does and should increase the cross section.

A simple exploratory luminosity calculation can be carried out for the case of a uniform hard sphere nuclear charge distribution by allowing contributions from within the ions but with an effective Z multiplied by $(b/R)^4$, where $b_i$ is the distance of the photon source from the center of the nucleus. The result is that with this finite density cutoff the two photon luminosity in the STAR measured equivalent pair mass range would increase by 44% over the sharp cutoff, and one can infer a proportional increase in the predicted perturbative Weizsacker-Williams pair cross sections.

The physical question is whether equivalent photons arising from within one the ions when the ions are not overlapping should contribute to the process. We have previously noted[9] that the requirement that final states be outside the nuclei may not be necessary for some final states such as lepton pairs. The smooth cutoff conventionally implemented by a momentum dependent form factor in QED calculations does not seem unreasonable.

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