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"MEASUREMENTS OF PAIR PRODUCTION AND ELECTRON CAPTURE FROM THE CONTINUUM IN HEAVY PARTICLE COLLISIONS"

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MEASUREMENTS OF PAIR PRODUCTION AND ELECTRON CAPTURE FROM THE CONTINUUM IN HEAVY PARTICLE COLLISIONS

Introduction

In peripheral collisions of high-Z systems at sufficiently high energies, large transient Coulomb fields are generated which lead to copious production of electron-positron pairs. The production cross sections have been calculated by several authors1-6 with results which differ significantly from each other. We have recently published results of measurements of electron-positron production cross sections and dependence on target atomic number (Z_T) for 200 GeV/u sulfur ions on Al, Pd, and Au.7 These results agree reasonably well with lowest-order QED calculations.4 However, it is anticipated that perturbative treatments may fail for sufficiently energetic, high-Z collision systems. Electromagnetic production of lepton pairs in peripheral collisions of ultrarelativistic heavy ions is fundamentally different from pair production by light particles because the coupling constant is strongly enhanced. For very heavy systems, such as 82Pb + 79Au, the coupling constant Zα becomes >0.5, where Z is the atomic number and α is the fine structure constant. Typical theoretical total cross sections applied to (Pb - Pb) collisions at expected Large Hadron Collider (LHC) energies and luminosities (~10^{26}/cm^2 sec) give single-electron pair production rates exceeding ~10^8/sec.8 As noted by Bertulani and Baur3 and several other authors,4,9 pair production in near, but non-central collisions of sufficiently high-Z systems explicitly violates unitarity in lowest-order perturbation theory. This has been interpreted as an indication that multiple pair formation could dominate single-pairs in such collisions.11 High backgrounds of these high multiplicity pairs may pose important problems at collider energies which have been recognized in recent workshops on QED test and experiment and detector designs for collider facilities.9,11 Even at SPS energies, these backgrounds may be significant. The expected total cross section for single electron-positron pairs for 160 GeV/u Pb + Au (taken from Z_p^2 scaling of our measured cross sections for 200 GeV/u S + Au) is 3300 barns. Most electron energies are low, but ≥30% are expected to lie above ~20 MeV/c. We propose two experiments to study (1) electron-positron pair production and (2) electron capture from pair production in collisions of 160 GeV/u Pb with thin light and heavy targets. These will be the first experiments in collision systems where low-order perturbative calculations are expected to fail. In the first part, we will extend our previous measurements of differential cross-sections for single pair production by 200 GeV/u S ions to measurements of single and multiple pairs produced by
Pb ions. These measurements will be carried out as before, parasitically with WA93, using extremely thin targets and relatively weak (0.1–0.5 T) magnetic fields, so as to minimally perturb WA93 data taking.

In the second part of the experiment, we will directly measure cross sections for atomic electron capture to the projectile ions. Some of the electrons created in pair production may be captured into bound states of the projectile, thereby, reducing its charge state by one unit. This process has been termed “Electron Capture from Pair Production.”\(^{12}\) It represents the only electron capture process which increases with energy, and as such, will dominate all others in the ultrarelativistic energy regime. Ions having undergone this process would be lost from storage-type accelerators such as heavy-ion colliders. The absolute cross sections for capture have been calculated by a number of authors with results which differ by as much as an order of magnitude.\(^{2-5,8,12}\) If the actual cross sections for electron capture are as large as some of the calculations predict, relativistic heavy-ion colliders would be luminosity limited by loss of the charge-changed ions produced at the beam overlap regions.\(^{8}\) At SPS energies, the capture process is dominated by capture from pair production with a small correction for radiative electron capture (REC). These measurements will be accomplished, using the beam line as a charge-state analyzer, by tuning for transport of one-electron 160 GeV Pb\(^{81+}\) ions and counting as a function of target Z and thickness.
EXPERIMENT I

Measurements of Electron-Positron Pair Production in Coulomb Collisions of 160 GeV/u Lead

The main goals of this portion of the experiment are measurements of the doubly-differential cross sections for single and multiple electron-positron pair production, $d^2\sigma/d\Omega dE_e$ and $d^2\sigma/d\Omega dE_{e^+}$, by 160 GeV/u lead ions on thin targets, along with energy and angle correlations. These measurements will be performed through uniform magnetic field separation and analysis of electrons and positrons detected in time coincidence in two arrays of discrete particle detectors as accomplished previously using sulfur ions.\(^7\) Since the experimental apparatus will be essentially the same as used previously (WA90, Oct. 1991), only a brief outline of experimental techniques will be repeated here. A schematic of the apparatus is given in Fig. 1. The targets and detectors will be mounted in a vacuum chamber located near the middle of a 1 meter long CERN dipole bending magnet inserted upstream of the WA93 experiment. The vacuum chamber will be coupled directly, with remotely removable thin plastic windows ($\leq 100 \mu m/cm^2$), to the CERN beam pipe. The chamber will be pumped to pressures of $\leq 10^{-5}$ Torr using turbo-molecular pumps mounted on upstream and downstream ends of the chamber. Thin targets of $^{13}$Al, $^{46}$Pd, and $^{79}$Au (0.1–5 mg/cm$^2$ thick) will be remotely positionable to allow for a variety of target elements and thicknesses. Targets will be fully removable without breaking vacuum to allow a straight-through path with a minimum diameter of 5 cm.

Low energy (0.5–20 MeV) electrons and positrons generated by ions in the targets will be separated in the nearly uniform vertical magnetic field and transported 180° along circular arcs to one of two identical arrays of discrete detectors mounted on either side of the ion beam in the plane containing the chosen target. A schematic of the apparatus with views from the top and along the beam axis is given in Fig. 2. For forward emitted electrons or positrons of a given momentum, horizontal displacement of a particle’s trajectory at the detector plane in such a geometry is closely proportional to its momentum and is only weakly dependent on launch angle, because of first-order focusing in the plane of dispersion.

The detector arrays are each composed of 41 separate circular (2 cm dia.) silicon surface barrier detectors with depletion depth of 300 μm. Thin detectors minimize sensitivity to background counts from gammas. Detectors in an array are arranged in five closely packed horizontal rows covering 52% of the area between the magnet poles on either side of the ion beam as shown in Fig. 2a. The arrangement extends horizontally from 3 cm to 25 cm from the target center, and 5.3 cm above and below the ion beam axis.
The limited vertical height of the array permits full azimuthal collection only for limited ranges of polar angles which vary from 0° to 25° for the innermost (low momentum) detectors to 8° for the outermost (high momentum) detectors. Our previous measurements indicate that nearly 85% of all pairs produced should lie within this angular acceptance. Figure 2a shows calculated, detector-plane end points for 3.5 MeV electrons in 0.18 T field. Figure 2b shows calculated trajectories expected for 1, 2, 4, and 6 MeV/e electrons ejected at 0°–20°. For emission inside a 45° cone, momentum resolution is dominated by finite detector size and spacing and varies from Δp/p = 30% for the innermost- to 6% for the outermost-detectors.

A large scintillator detector sensitive to minimum ionizing particles with a 3 cm diameter central hole will be mounted symmetrically about the beam axis 2 meters upstream of the spectrometer. Signals from this detector will be used to provide vetoes for detector noise counts generated by any high energy particles accompanying the primary ions, but lying in an extended halo >3 cm beyond the main beam axis. A second veto signal will be generated for similar halo and scattered high-energy particles lying less than 4 cm and more than 2 mm from the beam axis, by a quartz Cerenkov active collimator mounted several meters downstream of the vacuum chamber.

Signals from each positron and electron detector will be independently processed. Events will be triggered by coincidences between positron signals and full-energy lead ions. Data will be acquired and stored under control of a PC/CAMAC-based acquisition system (‘KMAX’), in which all event data is stored in list mode and selected event parameters are sorted on-line into histograms for real-time diagnostics.

Very thin targets will be used to maintain acceptable counting rates from KO electrons and to reduce multiple Coulomb scattering. Signals from the WA93 Zero Degree Calorimeter will be used in our experiment as in previous runs to identify, count, and provide timing for full energy projectile lead ions. These signals will be employed for normalization and for coincidence measurements with positrons and electrons detected in our magnetic spectrometer.

Interfering Signals

As noted in our previous proposal, the largest background signal in measurements of electrons and positrons is due to target atom electrons ejected in direct, binary collisions with the projectile. The resulting knock-on (KO) or 8-electrons were studied extensively in WA90 200 GeV/u sulfur runs using targets of C, Al, and Au. Results of these measurements of KO electron absolute yields, as well as energy and angular distributions, were compared with calculations based on relativistic Born approximation differential
cross sections and found to agree reasonably well (±35% for 1-17 MeV/c, within experimental uncertainty).

The expected and observed relatively large emission angles for low energy KO electrons allowed us to successfully reject the majority as backgrounds, especially for thin (≤1 mg/cm²) targets and in positron-electron-unsattered ion coincidence events. Total cross sections for both electron-positron pair production and KO electrons scale as the square of the bare projectile atomic number Z_p. Therefore, since momentum and angular distributions for both processes are expected to show only weak variations with projectile charge (i.e., S¹⁶⁺ vs Pb⁸²⁺), KO backgrounds will have essentially the same relative intensity as observed for sulfur ions. Lead ions will generate ~25 times more KO's than observed with sulfur. To avoid significant dead time and pile-up problems due to high KO singles rates, we will use targets approximately 1/3 of those used in the previous run with sulfur ions. These very thin targets will also virtually eliminate effects of multiple Coulomb scattering on measurements of low energy pairs, so that we anticipate extension of momentum measurements for positrons and electrons to below our previous cutoff of ~1 MeV/c. This will permit study of differences in dσ/dp for electrons versus positrons in the region of the expected maximum of the cross section at ~1 MeV/c. To ensure that KO backgrounds are treated properly, we will again study their energy and angular distributions in light targets of C and Al, as well as Pd and Au, with the 160 GeV/u Pb beam. These measurements will include determination of the KO multiplicity distributions as a function of electron energy.

To cover approximately 85% of the total cross sections, we will measure electrons and positrons at three magnetic fields (0.12, 0.18, and 0.45 T). Required beam time with each target will be determined by the relatively low counting rates for higher multiplicity events. Single electron-positron pair counting rates will be large. For a 1 mg/cm² Au target and 10⁶ Pb ion/spill, we expect to detect ~700 pairs/spill. The most recent calculations⁸ applied to 160 GeV/u Pb⁸²⁺ + Au collisions give double- and triple-pair cross sections, which are 7% and 1%, respectively, of the total cross section for single pairs. At each magnetic field setting, we expect to intercept ~50% of the total singles cross section with 52% collection/detection efficiency. To acquire sufficient statistics to test various theoretical predictions for pair multiplicity distributions will require ≥100 triple-pair events, or ~13 hours at each magnetic field. For 6–8 targets and 3 fields, measurements of single and multiple pairs, as outlined above, will take ~11–12 days of beam-on-target. Knock-on electrons detected in coincidence with unscattered Pb ions will also be measured for 3 magnetic fields and with 6–7 thin, most low-Z_T targets. Signal rates are expected to be 10–100 times larger than for pairs. Beam time required for the KO measurements is estimated
at ~2 days. Calibrations with beam should take ~1–2 days for a total of beam-on-target

time of 14–15 days), for this experiment.

References

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p. 325.
(1984); "New Experiments on Few-Electron Very Heavy Atoms," in Atomic Theory
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Physics, New York, 1985), p. 66; R. Anholt and H. Gould, "Relativistic Heavy-Ion
Atom Collisions," in Advances in Atomic and Molecular Physics," edited by D. Bates
Fig. 1 Schematic of electron positron pair apparatus indicating magnetic separation and analysis of electrons and positrons, detector arrays on side of target, identification, and timing of unscattered Pb ions using signals from WA93 Zero Degree Calorimeter, and various veto detectors.
Fig. 2a  End view of magnetic pair spectrometer showing projections of sample trajectories for 3.5 MeV/c KO electrons from the target to the detectors with end points indicated by points. Vacuum chamber containing detector arrays for positrons and electrons is mounted between pole tips of dipole magnet as displayed. Forward emitted pair electrons and positrons are nearly all collected on the detectors.
Fig. 2b  Top view of magnetic pair spectrometer showing projections of sample trajectories for 1, 2, 4, and 6 MeV/c positrons ejected at zero degrees (dark curves) and on a 20° cone to indicate first-order focusing effect.
EXPERIMENT II

Capture of Electrons from Pair Production in Collisions of 160 GeV/u Lead

Our aim is to measure the cross section for electron capture from the negative continuum in ultrarelativistic collisions. The question is of considerable theoretical importance insofar as it provides a test of QED under nonperturbative conditions. The results are of practical importance since the process may, in fact, limit the storage time in heavy ion colliders such as RHIC and LHC. A comparison between calculations for capture in Pb on Pb collisions at lower energies is given in Table 1. For the case of Pb (160 GeV/u) + Au, calculations by Strayer and Bottcher give \( \sigma_{\text{pair}} \) (\(^{207}\text{Pb}^{82+} \) 160 GeV/u) + Au = 50 b.\(^5\) To quote a recent paper by Bottcher and Strayer [Ref.6]

"Pair production with electron capture to one of the ions has not been measured at these energies (i.e., RHIC) and theoretical calculations at lower energies differ by an order of magnitude. The disagreement could be more than a factor of 100 for the highest RHIC energies. Thus there is a clear need to obtain definite capture measurements as soon as possible."

Table 1. Different capture calculations for collisions of Pb + Pb at an energy of 1.2 GeV per nucleon.

<table>
<thead>
<tr>
<th>Method</th>
<th>Reference</th>
<th>( \sigma_{\text{pair}} ) (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent Photon</td>
<td>Bauer 1987 (1)</td>
<td>2.8</td>
</tr>
<tr>
<td>Two Photon</td>
<td>Rhoades-Brown 1989 (2)</td>
<td>4.6</td>
</tr>
<tr>
<td>Distorted Wave</td>
<td>Becker 1987 (3)</td>
<td>0.3</td>
</tr>
<tr>
<td>Coupled Channel</td>
<td>Rumrich 1991 (4)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The concept of the experiment is quite simple and runs as follows. A thin target would be inserted far upstream of experiment WA93 (as per discussions with Per Grafstrom). The beam line for WA93, which had been tuned to \(^{207}\text{Pb}^{82+}\), would be then tuned to \(^{207}\text{Pb}^{81+}\) by increasing the magnetic fields by 1.2%. Using the signal from a thin scintillator or gas detector placed immediately upstream from the target as a normalization, the \(^{207}\text{Pb}^{81+}\) signal observed at WA93 is directly related to the desired capture cross section.

The absolute determination of \( \sigma_{\text{pair}} \) is not quite so simple because of competing processes in electron capture and loss. Other modalities for electron capture are
"mechanical" nonradiative capture (NRC) capture and radiative electron capture (REC). "Mechanical" capture can be shown to be small in this case [Ref. 7].

\[ \sigma_{\text{NRC}} (^{207}\text{Pb}^{81+} + 160 \text{ GeV/u}) + \text{Au} = 0.5 \text{b}. \]

Radiative electron capture, although significantly larger [Ref. 7], is also small compared to the estimated cross sections for capture from the negative continuum, i.e.,

\[ \sigma_{\text{REC}} (^{207}\text{Pb}^{82+} + 160 \text{ GeV/u}) + \text{Au} = 1.4 \text{ b}. \]

Hence, if capture to \(^{207}\text{Pb}^{81+}\) is observed, it should be predominantly due to capture from pair production. This can be checked by experiments using low \(Z\) targets where capture from pairs is suppressed relative to REC. Therefore, coincidence measurements with positrons should not be needed.

The limiting process is electron loss. Once an electron is captured by the ion in the solid target, there is a large probability that it will be re-ionized by a second collision in the target. The estimated loss cross section for an Au target is [Ref. 7]

\[ \sigma_i (^{207}\text{Pb}^{81+} + 160 \text{ GeV/u}) = 6 \times 10^4 \text{ b}. \]

Table 2 lists the relevant cross sections for Au, Al, and Be.

<table>
<thead>
<tr>
<th></th>
<th>Capture</th>
<th>Ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\sigma_{\text{pair}})</td>
<td>(\sigma_{\text{REC}})</td>
</tr>
<tr>
<td>Au</td>
<td>50</td>
<td>1.4</td>
</tr>
<tr>
<td>Al</td>
<td>1.4</td>
<td>0.23</td>
</tr>
<tr>
<td>Be</td>
<td>0.13</td>
<td>0.07</td>
</tr>
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Using these assumptions, we plot in Figs. 1–3 the expected charge fraction of \(^{207}\text{Pb}^{81+}\) as a function of target thickness for Au, Al, and Be targets. The sensitivities to variations in capture and loss cross sections are also indicated. It will be necessary to use several target thicknesses to separately determine the capture and loss cross sections. We propose to use six Au targets, ranging from 2 to 20 mg/cm\(^2\). We would also plan to run four Al targets
and four Be targets to test the $Z_T$ dependence of the cross sections. If we take, as an example, an 8 mg/cm$^2$ Au target and a 50 b cross section, we expect a probability of $6.5 \times 10^{-4}$ that an incident $^{207}\text{Pb}^{82+}$ ion will exit the target as $^{207}\text{Pb}^{81+}$ with a bound electron. If we assume $10^6$ ions/dump and 4 dumps/minute, this gives a count rate of $\sim 2500$/min.

To carry out this experiment would require 24 hours of dedicated beam time and the collaboration of WA93. We would request that this time be placed at the end of the WA93 run in 1994.

References


Fig. 1. Pb$^{81+}$ charge state fraction vs Au target thickness

A - Calculated using cross sections listed in Table 2 but not including REC.

A' - Calculated using cross sections from Table 2 including REC.

B - Changing the electron loss cross section by +30%.

B' - Changing the electron loss cross section by -30%.

C - Changing the electron capture cross section by -30%.

C' - Changing the electron capture cross section by +30%.
Fig. 2. Pb\textsuperscript{81+} charge state fraction vs Al target thickness

A – Calculated using cross sections listed in Table 2 but not including REC.

B – Calculated using cross sections listed in Table 2 including REC.
Fig. 3. $\text{Pb}^{81+}$ charge state fraction vs Be target thickness

A – Calculated using cross sections listed in Table 2 but not including REC.

B – Calculated using cross sections listed in Table 2 including REC.
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