Measurements of positrons from pair production in Coulomb collisions of 33-TeV lead ions with fixed targets

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Free positrons from electron-positron pairs produced by 33-TeV Pb^{82+} ions in Coulomb collisions with targets of carbon $[(CH)_x]$, aluminum, palladium, and gold have been measured to determine cross sections and momentum distributions. Upper limits have been established for contributions from multiple pair formation. Comparison with similar data taken for 6.4-TeV S^{16+} ions shows that cross sections scale as the product of the squares of the projectile and target nuclear charges. Positron momentum distributions for S^{16+} and Pb^{82+} ions on all targets are observed to be similar, but indicate a tendency for higher-energy positron emission for the Pb^{82+} projectiles. [S1050-2947(97)01711-3]

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I. INTRODUCTION

At ultrarelativistic energies, atomic collisions between heavy, highly charged atoms produce extremely intense, rapidly varying electromagnetic fields that, in turn, give rise to very large ionization cross sections, diminished electron capture cross sections, and copious lepton pair formation. Recent progress toward realization of energetic ion-ion colliders such as the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory and the Large Hadron Collider (LHC) at CERN has sparked renewed interest in electromagnetic phenomena at very high energies. Theoretical treatments of electron-positron pair production in high fields have progressed significantly over the last decade, while measurements of free pair production with accelerated beams of highly charged ions at relativistic energies have only recently become available [1–7]. Measurements of electron-positron pairs with the electron final state either unbound (free pair production), or bound on one of the colliding ions (electron capture from pair production), have been reported for heavy ions at relativistic (~1 GeV/nucleon) [1–3] and ultratrelativistic (~200 GeV/nucleon) [4,5] energies. Characteristic of electromagnetic interactions, the cross sections increase with collision energy. These heavy-ion collisions are fundamentally different from those historically receiving attention involving singly charged projectiles because the coupling constant $Z\alpha$, can be quite large ($\geqslant$0.5) in heavy systems. Lepton pair production in these systems is especially interesting because the collision strength can be varied continuously, from regions of low charge and energy, where past applications of low-order perturbative methods are suitable, to higher energy and charge regimes where first-order perturbative calculations are known to occasionally give unphysical results, and nonperturbative methods may be required [8,9].

We recently reported [4,5] results of measurements of electrons and positrons formed as pairs in peripheral collisions of ultrarelativistic sulfur ions with thin solid targets. Those data gave experimental angular and momentum differential cross sections for electrons and positrons that agreed relatively well with predictions of lowest-order perturbative calculations. This agreement was expected for 6.4-TeV sulfur ions, since the calculated probabilities for pair production were relatively small at all impact parameters. It was noted in Ref. [5] that the failure of perturbative calculations might be anticipated for significantly heavier collision systems and at higher impact energies, in which low-order perturbation terms would give pair production probabilities violating unitary at sufficiently small impact parameter. Several theoretical treatments have concluded that multiple pairs should be formed in single close collisions, with some disagreement on absolute magnitudes and on effects of the multiple-pair-forming channels on total cross sections [9–12]. Both perturbative and nonperturbative calculations have led to predictions of Poisson distributions for the number distributions of multiple electron pairs [9,11,13].

II. EXPERIMENTAL METHODS

Using 33-TeV Pb^{82+} ions from the European Laboratory for Particle Physics (CERN) Super Proton Synchrotron accelerator (SPS), we have measured yields and momentum distributions of positrons from electron-positron pairs generated in long-range Coulomb collisions. Electrons and positrons produced in thin targets of ‘‘carbon’’ $[(CH)_x]$, aluminum, palladium, and gold were separated and dispersed in a uniform-field magnetic spectrograph. Positrons were counted in an array of detectors covering a momentum range $p_+ = 1-12$ MeV/c. Figure 1 displays schematically the general layout of the experimental apparatus along the SPS H3 beam line. Halo particles accompanying Pb ions were detected in veto scintillator counters mounted both upstream and down-

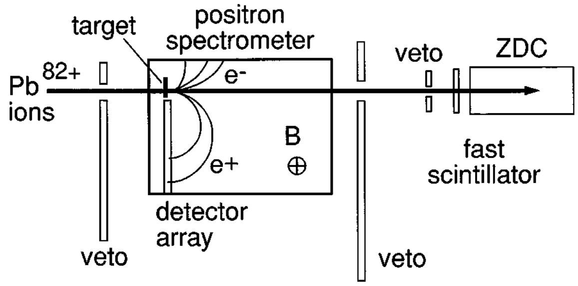

FIG. 1. Schematic diagram of the experimental apparatus, showing the uniform magnetic field positron spectrometer, halo particle veto counters, the ion beam fast counter, and the zero degree calorimeter (ZDC).

steam of the positron spectrometer. These permitted veto rejection of spurious backgrounds arising from fast halo particles penetrating the vacuum chamber and detectors.

Projectile ions passing through these very thin targets were mainly unaffected. Independent measurements [14] of total beam depletion gave a survival yield of 99.97% of the $^{208}Pb^{82+}$ ions in the thickest gold target. The primary ions ($\sim 10^5 - 10^6$/spill) continued downstream where they were used in a large nuclear physics collaboration experiment, WA98 [15]. Signals from WA98 fast scintillator counters and a zero degree calorimeter (ZDC) were used to identify, count, and provide timing for full-energy lead ions detected in coincidence with electrons or positrons from our targets, eliminating contributions from nuclear collisions.

In previous measurements with 6.4-TeV sulfur ions [4,5], both the electrons and positrons constituting pairs were simultaneously measured using two arrays of detectors located on opposite sides of the target. Attempts to measure pair electrons were abandoned in the currently reported measurements because extrapolations of the sulfur data (and, independently, calculations based on relativistic Born approximation differential cross sections for binary ion-electron collisions [16]), predict high probabilities for simultaneous emission of a direct knock-on (KO) electron from the targets for every pair-producing collision. Separation and identification of KO electrons other than by statistical means, for example, through correlations of energy and angle, then become impossible. We therefore restricted measurements and analyses of electron-positron pair components to positrons from thin (e.g., $\leqslant 1.5$ mg/cm^2 Au) targets.

Figure 2 shows a schematic diagram of the positron spectrometer viewed along the beam axis (a) and from above, perpendicular to the plane of dispersion (b). With minor modifications, the experimental arrangement has been described in greater detail in Ref. [5]. Positrons emitted forward near the beam axis followed spiral trajectories in a uniform 0.18-T vertical magnetic field and intercepted the detector plane at horizontal displacements (x), which were closely proportional to their momenta. The x values obtained were only weakly dependent on launch angle due to first-order focusing in the plane of dispersion at 180°. Particle motion in the vertical direction was unaffected by the magnetic field, so that vertical displacement (y) at the detector plane corresponded to the vertical component of the transverse momenta. Positrons bent through $\sim 180°$ were directed onto an array of 81 separate circular (2 cm diameter) silicon

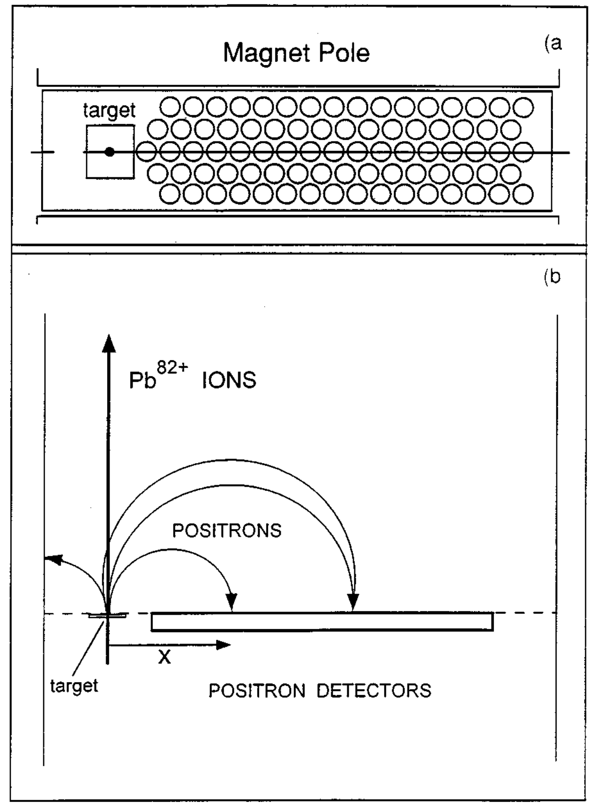

FIG. 2. Schematic diagram of the positron magnetic spectrometer. (a) End view, along the ion beam axis, showing the target and the array of 81 Si surface barrier solid-state detectors. (b) Top view, showing example electron and positron circular trajectories in the plane of dispersion and indicating first-order focusing for forward emitted positrons.

surface-barrier detectors (depletion depth 300 μm). The circular detectors were arranged in five horizontal rows, covering 52% of the available area as shown in Fig. 2(a). The array extended horizontally from 3 to 36 cm from the ion-beam axis, intersecting the center of the target, and vertically, 5.3 cm above and below the beam axis. The apparatus thus constituted a 180°, homogeneous field magnetic spectrometer with 81 discrete counting channels, designed for simultaneous detection of multiple positrons separated by at least 0.66 MeV/c corresponding to the spatial separation of individual detectors.

Positron counts were stored as a function of detector positions for a detected momenta range of 1.0–12.0 MeV/c over the full array of detectors. The limited vertical height of the array permitted complete azimuthal collection only for restricted ranges of polar angles that varied from ~ 0 to 25° for the innermost (low momentum) detectors to ~ 0 to 5° for the outermost (high momentum) detectors. Previous measurements of positron angular distributions for S ions showed agreement with calculations within a similar angular range [5]. The fraction of (1–12 MeV/c) positrons accepted by the detector array is estimated from these calculations to be $\sim 75\%$ of the total.

A 75-μg/cm^2 target of polypropylene $(CH_2)_x$ was used to investigate the KO electrons and their effects as backgrounds and to determine efficiencies for detection and acquisition under beam-on conditions at electron energies characteristic of the positrons measured. The polarity of the magnetic field was reversed to transport electrons instead of positrons to the detector plane. For low Z_T targets, the electrons ejected are almost entirely due to target KOs. Less than ~1% arise from pair production in $(CH_2)_x$ targets. Based on a direct comparison of measured KO yields with Monte Carlo calculations [16] using relativistic Born approximation differential cross sections for point nuclei and tracking of electron trajectories through the measured magnetic field, the absolute detection efficiency (assuming equal positron and electron detection efficiencies [17]) averaged over detectors in the array was (37±8)%.

A positron hit on any one of the 81 independent detectors occurring in time coincidence with a full-energy lead ion measured in the ZDC and in anticoincidence with signals from veto wall scintillation counters constituted a valid event. Latch registers stored all positron signals occurring within 100 nsec following the initiation of an event. Multiple counts of M positrons within the 100-nsec window occurred—from detection of real positrons from M-fold positron events from multiple pairs generated in a single collision, from accidental coincidences of multiple collisions, and from electronic cross-talk among detectors, signal lines, preamplifiers, and discriminators. Randomly distributed apparent double ($M=2$) hits were observed for low-Z_T [$(CH_2)_x$ and Al] targets to be proportional to single hits, at ~2.2% of the single-hit rate. Real multiple-pair generated signals of multiple positron hits are expected to be sensitive to target atomic number, and should be insignificantly small for low-Z_T targets. The observed constant 2.2% yield was therefore interpreted as indicative of the level of electronic cross-talk, an interpretation confirmed by later tests of electronic coupling of test signals among detectors and signal lines located inside the spectrometer vacuum chamber.

III. RESULTS AND DISCUSSION

To investigate pair production target and projectile dependences, the raw measured positron yields per ion for S and Pb ions on all targets were obtained by integration of single-hit counts over 1–12 MeV/c. These yields were corrected for differences in detector efficiencies and for projectile energy per unit mass (γ) (assuming $\sim\ln^3\gamma$, as predicted by perturbation theory [18]). Fits of the corrected yields to power-law dependences for Z_p and Z_T as $\sim Z_p^P Z_T^{P'}$ gave $P=2.0\pm0.1$ and $P'=2.03\pm0.03$, in agreement with $\sim Z_p^2 Z_T^2$ predicted by perturbation theory. We note that free pair production measurements made at much lower collision energies have also shown an approximate $\sim Z_p^2 Z_T^2$ behavior. Measurements by Belkacem *et al.* [3], of free pair production by 1.0-GeV/nucleon and 1.3-GeV/nucleon La^{57+} and U^{92+} on Cu, Ag, and Au targets gave projectile and target charge dependences of $\sim Z_p^P Z_T^{P'}$, with $P=1.53\pm0.8$, and $P'=2.15\pm0.25$. It should be noted, however, that for these collision energies, first-order perturbation calculations significantly disagree with measured absolute free-pair cross sections [3].

After correcting for angular acceptance variations with momentum as in Ref. [5], for individual detector response efficiencies, and for areal coverage, yields of single positrons

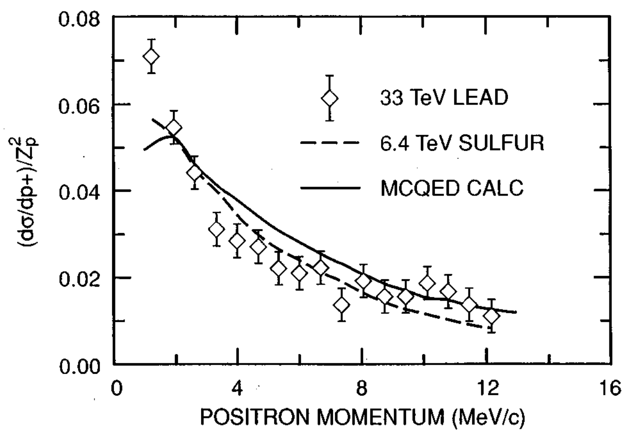

FIG. 3. Measured positron momentum differential cross sections dividied by Z_p^2 for 33-TeV Pb+Au, compared with cross sections for 6.4-TeV S+Au and with MCQED calculation results. Sulfur cross sections have been scaled to 160 GeV/nucleon ($\gamma=168$) from 200 GeV/nucleon ($\gamma=212$) according to $\ln^3\gamma$. The scaled differential cross sections are given in barns per MeV/c.

were binned according to momentum and converted to differential cross sections. Relative momentum distributions for all targets were observed to be the same within statistical error as predicted by lowest-order perturbative calculations [18]. In Fig. 3, we compare single positron ($d\sigma/dp+$) for 33-TeV Pb ions on Au, with data taken previously for 6.4-TeV S ions, and with lowest-order QED theory. The sulfur data have been scaled from $\gamma=212$ to $\gamma=168$ as $\ln^3\gamma$, and both S and Pb+Au $d\sigma/dp+$ are divided by Z_p^2 ($Z_p=16$ and 82, respectively). The two distributions are similar, but exhibit an increase in cross section above ~8 MeV/c for Pb ions, giving substantially better agreement with Monte Carlo evaluation of lowest-order QED terms (MCQED) as calculated in Ref. [19].

The measured Pb+Au $d\sigma/dp+$ shown in Fig. 3 also exhibit an unexplained enhancement of ~30–35% above MCQED theory and S+Au measurements for $p_+=0.9$–1.6 MeV/c. An increased background contribution of low-energy, scattered KO electrons for Pb ions would account for such a difference. However, we note that all targets (Z_T=‘‘6,’’13,47,79) gave similar results. Positron yields scale as $\sim Z_T^2$, while KO yields scale as $\sim Z_T$. Relative KO backgrounds should vary by greater than a factor of ten for these targets. The absence of observed differences in positron momentum distributions with the various targets is strong evidence that there can be only very small contributions of KO backgrounds anywhere in the positron spectra, and therefore argues for a real positron momentum distribution variation with projectile Z_p. Why the relative momentum distribution should vary with Z_p and not Z_T is unexplained.

Integration of measured $d\sigma/dp_+$ over 1–12 MeV/c gives a cross section of 2035±475 b for 33-TeV Pb^{82+}+Au. This is to be compared with 78±20 b for 6.4-TeV S^{16+}+Au for the same momenta. The corresponding MCQED results are 1955 b for Pb+Au and 85 b for S+Au. The errors quoted include statistical and background correction errors and estimated uncertainties in detection and acquisition efficiencies, but do not include any estimate of errors due to corrections

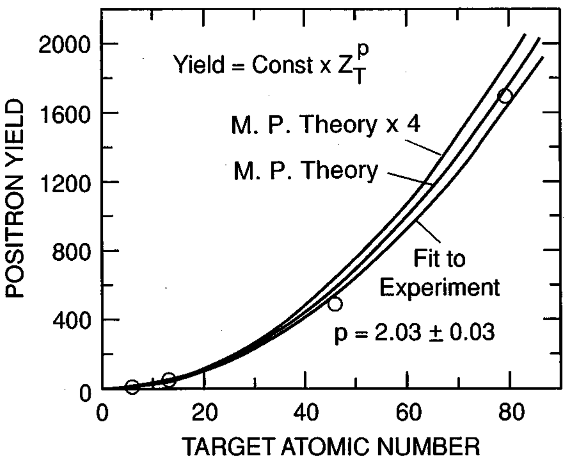

FIG. 4. Measured positron yields per ion ($p_+=1-12$ MeV/c) for 33-TeV Pb ions as a function of target atomic number Z_T. The solid curves represent, as indicated, results of a power law fit ($\sim Z_T^{P'}$) to the data, with $P'=2.03\pm0.03$, yields calculated from theoretical calculations of Ref. [21], and the effects of increasing the predicted multiple-pair yields (M. P. THEORY) by a factor of 4.

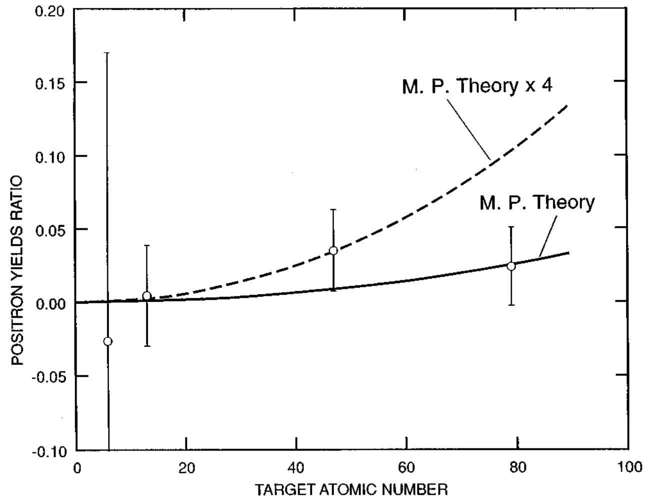

FIG. 5. Ratios of measured positron yields/ion ($p_+=1-12$ MeV/c) for double-to-single multiplicity hits on the detector array. Solid curve displays calculated ratios, based on theoretical cross sections from Ref. [21] for single and multiple pairs and assumes completely uncorrelated momenta and angles of the emitted positrons. Dashed curve shows the effect of increasing the theoretical multiple-pair contributions by a factor of 4 (M. P. THEORY $\times$4).

made for incomplete angular acceptance.

We note that previous S ion measurements of coincident electrons and positrons have indicated that the particles share the pair energy in a very uncorrelated way, contrary to some theoretical results [20], that predict substantial correlation among components of multiple pairs. We have assumed that positron momenta were completely uncorrelated in the analysis for multiple-pair effects that follows.

Multiple-pair contributions to total pair production were investigated by two methods. In the first, the total yields of positrons, counted as single hits on the detector array, were measured in precisely the same way for targets of $(CH_2)_x$, Al, Pd, and Au. Target thicknesses were chosen to maintain constant, low positron counting rates for all targets to avoid system dead time variations. The overall probability of detecting any emitted positron was low (~10%), so that, if the individual positrons were uncorrelated in momenta, single-hit additions to the total yield from double pairs would occur at approximately twice the rate of double-pair production. Triple pairs would add at ~3 times the triple pairs rate, etc.

As noted above, single-pair yields scale very nearly as the product of the squares of the charges of the colliding ions (see Fig. 3). However, multiple-pair yields should scale approximately as $\sim Z_T^{2M}$, where M is the pair multiplicity, i.e., $M=2$ for double pairs. Theoretical calculations of the strength of multiple pair production vary, but generally predict for the 160-GeV/nucleon Pb^{82+}+Au collision system ~2–5% double pairs compared to single pairs, falling to ~0.2–0.5% for triple pairs. A substantial contribution from multiple pairs to single-hit positron yields should then be manifested as a deviation from strict $Z_p^2 Z_T^2$ scaling. Figure 4 shows the results of fitting measured single-positron yields to $\sim Z_T^{P'}$, $P'=2.03\pm0.03$. The curve marked ''M. P. THEORY'' displays results based on multiple-pair cross-section calculations by Güclu *et al.* [21], assuming uncorrelated momentum independence of all the ejected positrons. The curve marked ''M. P. THEORY $\times$4'' indicates the effect of increasing the multiple-pair (higher-order $Z_T^{P'}$ terms) components by a factor of four over the theoretical value. Our results agree with the calculations [20,21], but also include the possibility of no multiple pairs.

The second method for investigating multiple pairs was more direct. Ratios of yields of double counts to single counts, $R(M=2/M=1)$, were measured and corrected for the 2.2% constant electronic cross-talk and for the total efficiency for counting one and two emitted positrons under the assumption that momenta are completely uncorrelated. Results are displayed in Fig. 5 as a function of Z_T. The experimental results support very low multiple pair production with a slight rise for heavy targets. The solid curve in Fig. 5 marked ''M. P. THEORY'' indicates the predicted [21] variation in $(M=2/M=1)$ ratios as a function of Z_T. If the multiple-pair contribution is increased by a factor of four above these calculation results, the ratios would behave as indicated by the dashed curve. The experimental results for Pb+Au $R=(2.4\pm2.6)$% agree with theory and set an upper limit of ~5% for the maximum relative fraction of multiple pairs to total pair production, under assumptions made of uncorrelated positron momenta and binomial M-pair distributions.

IV. CONCLUSION

In summary, we have measured positrons emitted in electron-positron pair forming collisions of 33-TeV Pb^{82+} ions with targets of $(CH_2)_x$, Al, Pd, and Au. Results of these measurements have been compared with similar data for 6.4-TeV S^{16+} ions and the same targets. The positron momentum distributions for S and Pb ions are observed to be approximately the same over the 1–12 MeV/c detected momentum range, except for enhanced production at very low momentum (<2 MeV/c) and at high momentum (>8 MeV/c) for

Pb ions. Yields from differential cross sections integrated over $1-12$ MeV/c scale as $Z_P^{2.0\pm0.1}$, as predicted by perturbative calculations. We observe for both the S and Pb ions that the yields per ion of $(1-12\,\mathrm{MeV}/c)$ positrons scale as Z_T^2, indicating that contributions from multiple pair formation (higher-order processes) are a statistically insignificant contribution to the total positron yield in these collisions. It would require a double-pair cross section three to four times higher than predicted by theory (where yields scale $\sim Z_T^4$) to produce significant deviation from Z_T^2 scaling, beyond our statistically determined result of $Z_T^{2.03\pm0.03}$. Measurements of ratios of observed yields of multiple-hit positrons to total positrons as counted in the discrete detector array also confirm very low average probabilities for production of multiple pairs. Under an assumption of complete lack of momentum or angular correlation for positrons emitted in multiple-pair events, we estimate from the data that the sum of all multiple pairs contributes $\lesssim 5\%$ of total pair production in 33-TeV Pb+Au collisions.

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