# Measurement of Electron Capture from Electron-Positron Pair Production in Relativistic Heavy Ion Collisions

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We have used a novel new spectrometer to make the first observation and measurement of electron capture from $e^+$-$e^-$ pair production in relativistic heavy ion collisions. For a 0.96 GeV/nucleon $U^{92+}$ beam the cross section for a Au target is 2.19(0.25) b, and the target $Z$ dependence is $Z_t^{2.8\pm0.25}$. We also measured the energy and angular distributions of the positrons, and for comparison, the cross section for $e^+$-$e^-$ pair production without capture is 3.30(0.65) b.

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We report the first observation and measurement of electron capture from electron-positron pair production in relativistic heavy ion collisions. This is the process in which an electron-positron pair is produced by the strong transient electromagnetic field of a relativistic atomic collision and the electron emerges from the collision *bound to the ion* [1].

Electron capture from pair production has two unique properties. First, its cross section will increase with increasing collision energy due to increased pair production in the stronger fields [1,2]. Second, capture from pair production can take place between two bare ions because it requires no electron in the initial state. As a result of these properties (and since the cross sections for other electron capture processes—radiative electron capture and nonradiative capture—decrease rapidly with increasing energy [2,3]), electron capture from pair production will be the dominant electron capture mechanism at highly relativistic energies and may limit the lifetime of stored beams of colliding bare ions in relativistic heavy ion colliders [4].

Since 1984, a number of calculations of the cross sections for electron capture from electron-positron pair production have been published [4–7]. Different techniques were used, producing results that are in disagreement with each other. Until now, no experimental measurement has been made to test the theoretical predictions, or even the existence of this process.

Figure 1 shows a schematic of our experiment, which was performed at Lawrence Berkeley Laboratory's Bevalac accelerator using 0.956 GeV/nucleon $U^{92+}$ (bare uranium ions) incident on thin, fixed targets of Au, Ag, Cu, and Mylar. The experimental signature for capture from electron-positron pair production is the capture of the electron, changing the charge of the $U^{92+}$ to $U^{91+}$, in coincidence with the detection of the emitted positron. The $U^{91+}$ is magnetically separated from the main $U^{92+}$ beam, and each charge state is detected, at the end of the

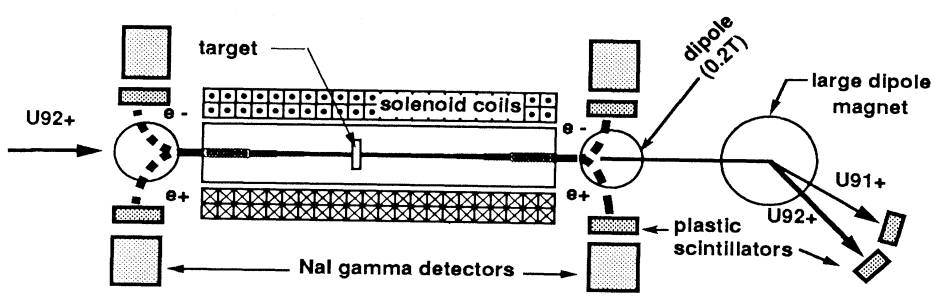


FIG. 1. Schematic of the experiment. See text for details.



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beam line, by a plastic scintillator-photomultiplier detector. The positron is detected, and its energy is measured by a plastic scintillator-photomultiplier detector.

The $U^{92+}$ ions pass through the fixed target located inside and slightly upstream from the center of the advanced positron spectrometer which is used to measure the energy and angular distribution of the positrons (as well as any electrons) emitted from the target. The advanced positron spectrometer contains a solenoid magnet with a dipole magnet at each end. The solenoid generates a strong ($B=0.8$ T, maximum), but adiabatically decreasing, longitudinal magnetic field that transports the positrons and electrons away from the target and, most importantly, converts much of the positron (electron) transverse motion into a longitudinal motion with respect to the axis of the solenoid. At each end of the solenoid (forward and backward), a dipole magnet deflects the positrons and the electrons in opposite directions, into detectors.

This combination of magnetic fields, together with careful field shaping in the solenoid-dipole interface region, yields a very high acceptance for electrons and positrons emitted both forward and backward with respect to the beam direction. Tests of the advanced positron spectrometer using heavy ion beams and radioactive sources show an acceptance close to unity for emission angles of up to 75° forward and backward. This acceptance is independent of the electron or positron energy in the energy range of interest (100 to 2500 keV).

For a given positron (electron) energy, larger emission angles result in a longer time of flight through the strong field of the solenoid, and this time of flight is used to determine the emission angle with respect to the beam direction. Four plastic scintillator-photomultiplier detectors (two forward and two backward), used to detect the positrons (electrons) and to measure their energy, are also used to measure their time of flight. The timing reference for the positron is the uranium ion that produced the positron (charge changed to $U^{91+}$ by the capture of the accompanying electron), detected at the end of the beam line. The energy resolution of the positrons (electrons) is about 17% and the angular resolution is about 15°.

The initial discrimination between positrons and electrons is made by the dipole magnets that deflect the positrons and electrons in opposite directions. Additional discrimination is made by detecting one of the two 511 keV positron-annihilation photons emitted back to back in the plastic scintillator in which the positron is stopped. The 511 kev photon is detected using a NaI detector set behind each of the four plastic scintillators in the advanced positron spectrometer. The detection efficiency of 511 keV photons by the NaI detector is measured to be 42% with approximately 60% of the photons appearing as a narrow single peak and the remainder as a broad Compton distribution. In our data analysis, we use only the narrow peak. This gives an overall positron detection efficiency of 25%.

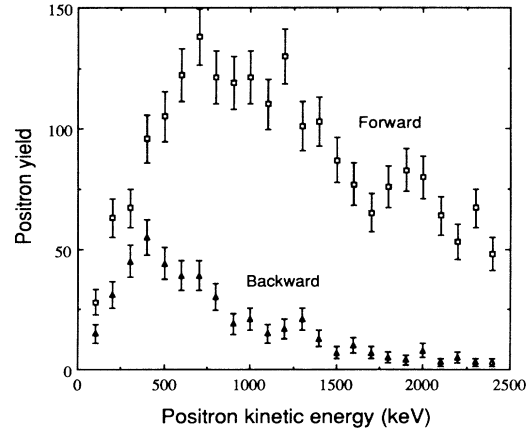


FIG. 2. Yield of positrons vs positron kinetic energy measured for electron capture from pair production by 956 MeV/nucleon $U^{92+}$ beam on a Au target. Each data point is an integration over all angles between 0° and 75° (forward and backward) with respect to the beam direction and over an energy interval of 100 keV.

The additional discrimination provided by the 511 keV photon is important, because at 1 GeV/nucleon, an average of 3 to 4 knockon electrons (delta rays) with an energy above 100 keV are ejected from a 1 mg/cm$^2$ gold target by each uranium ion, while only one positron from the same target is expected for every $10^6$ uranium ions. Roughly 0.2% to 0.3% of these knockon electrons backscatter from the electron scintillator into the positron scintillator-detector, simulating a positron. With the addition of the 511 keV photon, we accept only about 1 in $10^8$ (knockon) electrons.

Figure 2 shows the observed energy spectra of the positrons emitted in coincidence with the $U^{91+}$, produced by a 0.956 GeV/nucleon $U^{92+}$ beam incident on a 1 mg/cm$^2$ Au target. The data for the forward and backward directions have been integrated over emission angles of 0° to 75° and 105° to 180°, respectively. The two spectra are taken simultaneously and are therefore normalized to the same number of incident uranium ions. The spectra show a relative lack of low-energy positrons. This is due to the repulsion of the positrons by the gold target nuclei, which are at rest in the laboratory frame. The forward positron energy spectrum displays a broad maximum around 800 keV while the backward spectrum displays a maximum around 400 keV. Comparing the two spectra bin by bin suggests that positrons emitted at higher energies are also emitted at smaller (more forward) angles.

This relation is seen more clearly in Fig. 3 which shows the measured yield of positrons as a function of the positron emission angle (with respect to the beam direction) for different positron energies. The positrons with kinetic energies higher than 1800 keV are emitted preferentially at angles smaller than 40° while positrons with energies

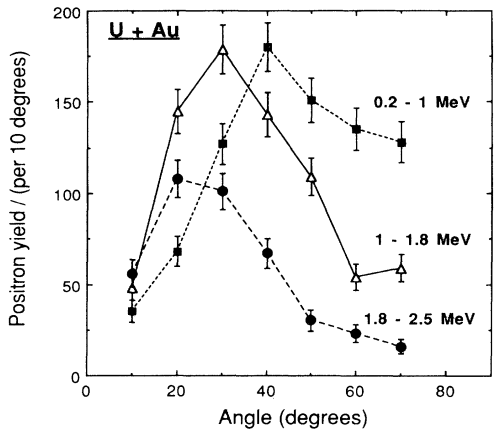


FIG. 3. Yield of positrons vs positron emission angle with respect to the beam direction for positron kinetic energies between 0.2 and 1 MeV (■), 1 and 1.8 MeV (△), and 1.8 and 2.5 MeV (●), respectively. Each data point is the result of an integration over an angular interval of 10°.

lower than 1000 keV are emitted preferentially at larger angles. This angular dependence agrees qualitatively with predictions based on perturbation theory for capture from pair production where the electron is captured by the projectile [5]. In contrast, the positron angular distribution from the free pair production (electron-positron pair production *without* capture of the electron) at this energy is predicted, by the same theory, to have a maximum at zero degrees [8,9].

Our measured total cross section for capture from pair production by a 0.956 GeV/nucleon $U^{92+}$ on a gold target is 2.19(0.25) b. The major contributions to the uncertainty, shown in parenthesis, are statistics (0.1), target thickness measurement (0.1), and possible systematic effects (0.2). We obtain a cross section of 3.30(0.65) b for the free pair process (for this process the positron is detected in coincidence with the $U^{92+}$). The larger uncertainty for free pair production is due to a larger background.

We find it striking that, at 1 GeV/nucleon, the electron of the electron-positron pair is almost as likely to emerge from the collision bound to the uranium ion as it is to emerge free. A calculation based on perturbation theory [5], and summed over all final bound states, yields a value of 1.01 b, which underestimates the measured total cross section for capture from pair production by $U^{92+}$ in Au by about a factor of 2.2. Recently, a nonperturbative, coupled-channels calculation of capture from pair production has been published [7] for Pb on Pb at 1.2 GeV/nucleon. To the best of our knowledge, a coupled-channels calculation for 1 GeV/nucleon $U^{92+}$ on Au has not yet been performed, making it difficult to compare our measurement to this calculation. (Using scaling from perturbation theory to extrapolate the results in Ref. [7] to U on Au gives a value that overestimates our measured cross section by about a factor of 2.) Our measured cross section for free pair production by $U^{92+}$ in Au is not in agreement with the value of 5.1 b of Becker, Grün, and Scheid [8] or the value of 1.25 b of Decker [9].

The total cross sections for capture from pair production for 0.956 GeV/nucleon $U^{92+}$ on Ag, Cu, and Mylar targets are 0.485(0.058), 0.129(0.019), and 0.0041(0.0025) b, respectively. A least-squares fit to these data shows that the cross section varies with the target atomic number $Z_t$ roughly as $Z_t^{2.8\pm0.25}$, which is not in good agreement with a $Z_t^2$ dependence predicted by perturbation theory for a bare ion on a bare target. This $Z_t$ dependence is, however, consistent with the nonperturbative coupled-channels calculation [7].

A false signature of the capture from pair production process can originate from a free pair production and, in the same collision, capture by the $U^{92+}$ of a target electron by radiative electron capture (REC) or nonradiative electron capture (NRC). REC is the capture of a target electron by an ion with simultaneous emission of a photon, and NRC is the radiationless capture of an electron initially bound to a target atom [3]. At 1 GeV/nucleon pair production is thought to occur at extremely small impact parameters (of the order of the Compton wavelength or smaller) where NRC is the main capture process for high-$Z$ targets [2]. In this case, the background would be expected to scale as $Z_t^7$ where a factor of $Z_t^5$ comes from the probability for NRC [2] and a factor of $Z_t^2$ comes from free pair production [10,11]. Our observed $Z_t^{2.8}$ dependence for capture from pair production sets a limit to the contribution from this background. Using measured NRC cross sections [3] we find a limit of 6% for the contribution of these events to our measured cross section for the Au target and still lower limits for the Ag and especially the Cu and Mylar targets.

In summary, we report the first measurement of electron capture from pair production. For 1 GeV/nucleon $U^{92+}$ on Au, the electron of the pair is found to be almost as likely to emerge from the collision bound to the $U^{92+}$ ion as to emerge free. The cross section varies approximately as $Z_t^{2.8}$, where $Z_t$ is the target atomic number. Both of these results are in disagreement with perturbation theory.

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