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Electron capture from pair production by Au^{79+} at 10.8 GeV/nucleon

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Cross sections for electron capture from pair production by 10.8-GeV/nucleon ($\gamma=12.6$) bare Au^{78+} ions have been measured in Au, Ag, Cu, and Al targets. These measurements can be compared with calculations used to predict beam lifetimes in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory and Large Hadron Collider at CERN. Experiment and calculations are compared. [S1050-2947(98)06808-5]

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I. INTRODUCTION

Electron capture from pair production is the process in which an electron-positron pair is produced in the strong transient electromagnetic field of a relativistic heavy ion atomic collision (no nuclear contact), with the electron emerging from the collision bound to the ion [1–3]. This process can take place between two bare ions, resulting in a charge change of one of the ions. It is predicted [4–6] to account for more than half of the beam loss for bare Au^{79+} ions in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and for bare Pb^{81+} ions at the Large Hadron Collider (LHC) at CERN.

For the RHIC, with four interaction regions, calculated capture from pair production cross sections of 89 b [7], 117 b [6], 144 b [8], and 192 b [9], added to an electromagnetic dissociation cross section of 95 b [6] and a nuclear collision cross section of 8 b, yields a luminosity half-life for the RHIC of 7.8–5.1 h [10]. For the LHC, with one interaction region but higher energy, the calculated luminosity half-life is between 7.8 and 5.5 h [11]. If the actual capture from pair production cross sections were much larger than calculated, the performance of the RHIC and LHC could be compromised.

Capture from pair production cross sections have been measured only in the 1-GeV/nucleon energy range (Lorentz factor $\gamma\approx 2$) [1–3]. In this low-energy range the cross section is increasing rapidly with energy and cannot be reliably extrapolated to the RHIC and LHC energies. The RHIC will collide 100-GeV/nucleon Au beams and the LHC 2.76-TeV/nucleon Pb beams, equivalent to a fixed target γ of 2.3×10^4 and 1.8×10^7, respectively. At $\gamma\approx 2$ calculations [12–14] differ from experiment [1–3] by a factor of 2 or more. Calculations made to predict the RHIC and LHC lifetimes [6,8,15] use approximations that are valid only for $\gamma\gg 1$ and hence cannot be compared to experiments done at $\gamma=2$. The calculations that have been performed to date are therefore either untested or in disagreement with experiment.

II. EXPERIMENTAL METHOD

We directly measure the cross section for electron capture from pair production at 10.8 GeV/nucleon ($\gamma=12.6$). This energy is high enough to test most calculations used to predict cross sections for electron capture from pair production at the RHIC and LHC. Our experiment uses Au^{79+} ions as the projectile and thin foils of Au ($Z_t=79$), Ag ($Z_t=47$), Cu ($Z_t=29$), and Al ($Z_t=13$) as fixed targets. The experiment (E892) was performed at the Brookhaven National Laboratory's Alternating Gradient Synchrotron in (primary) cave *D*.

The signature for capture from pair production is the observation of a positron emitted at the target in coincidence with a charge change of the Au^{79+} projectile to Au^{78+}. Measurement of the charge change is described in Ref. [16]. The positrons emitted at the target are magnetically guided and separated from the many electrons that are scattered from the target by the Au projectile. This is done with the Advanced Positron Spectrometer (APS), of which a detailed description can be found in Ref. [3].

The positron is detected and its kinetic energy, which extends to beyond 10 MeV, is measured by a plastic scintillator-photomultiplier detector. The positron annihilates in the plastic scintillator, producing a pair of 511-keV photons. The plastic scintillator is nearly transparent to the 511-keV photons and one of the photons is detected by a NaI-photomultiplier detector located behind the plastic scintillator. The trigger for the experiment is the coincidence detection of the 511-keV photon, the positron, and, with appropriate delays, the (charge changed) Au^{78+} ion, downstream.

III. DATA ANALYSIS

The 511-keV photon peak in the pulse height spectra from the NaI-photomultiplier detector (Fig. 1) are the main data

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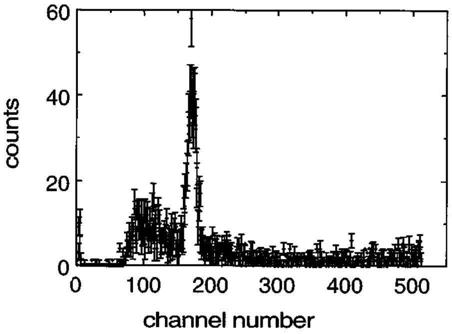

FIG. 1. Positron annihilation following electron capture from pair production by 10.8-GeV/nucleon Au^{79+} in an aluminum target. The peak is from 511-keV photons, produced by the annihilation of the stopped positron. The spectra from Cu, Ag, and Au targets have smaller background.

used to determine the capture from pair production cross section. The counts under the 511-keV peak are summed, the background is subtracted, and they are normalized to the number of incident ions and target thickness. The resulting cross sections are corrected for: the acceptance of the APS; detection efficiency of the 511-keV photons; electronic and detector dead time; and ionization of the (charged changed) Au^{78+} projectile, by the target.

The positron angular distribution is forward peaked (at roughly $1/\gamma$) resulting in an acceptance of close to 100% for the APS. The efficiency for the NaI detector to detect a 511-keV photon, produced by positron annihilation in the plastic scintillator, is measured to be 22% and is mostly determined by the solid angle subtended by the NaI detector. Approximately 70% of the detected photons appear 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 15.5%. The measured efficiency was tested and found to be the same before and after our data taking.

Positrons with different energies strike the plastic scintillator in different locations, possibly resulting in slightly different detection efficiencies for their 511-keV annihilation photons. We tested for any significant effect by varying the magnetic field in the APS that deflects the positrons into the scintillator so as to change the position that the positrons strike the plastic scintillator. We then looked for changes in the *positron energy spectrum* (which would indicate that more photons from the lowest- or highest-energy positrons were not being detected). No effect was observed within an uncertainty that we include in our experimental error. We estimate a total experimental calibration uncertainty, including uncertainties in NaI detector dead time (due to high γ ray background in the experimental area), collection efficiency, detector efficiencies, and acceptance of 15%.

We correct for ionization of Au^{78+} in the target using measured cross sections from Ref. [16]. The experiment described in Ref. [16] was done under the identical conditions as this experiment and used the same charge-state analysis and detection apparatus. The uncertainty in the ionization correction contributes less than 2% to our experimental uncertainty.

Target thicknesses are measured by weighing and for the thinnest targets also by α particle energy-loss measurement. The uncertainty in the target thickness contributes approximately 7% to the experimental uncertainty. Most of the targets used in this experiment are the identical targets used in the experiments in Refs. [1–3].

TABLE I. Cross sections for electron capture from pair production for 10.8-GeV/nucleon Au^{79+} (cross section in barns).

Z_t	Experiment	Becker, Grün, and Scheid[a]	Rhoades-Brown, Bottcher, and Strayer[b]	Baltz, Rhoades Brown, and Weneser[c]
79	8.8 (1.5)	10.1	10[d]	12.2
47	4.4 (0.73)	3.6		
29	1.77 (0.31)	1.36		
13	0.28 (0.052)	0.27		

[a] Interpolated from Fig. 3 of Ref. [12] (which includes *K*- and *L*-shell capture) plus 0.62 b added for higher shells.

[b] From Fig. 2 of Ref. [8]. There is a large uncertainty in reading this figure.

[c] Reference [15].

[d] Estimated.

IV. SYSTEMATIC ERRORS

A possible systematic error arises from the detection of a positron from free pair production (pair production without electron capture) in coincidence with the capture of an electron from an atom in the target [2,3]. The captured electron may be captured from the target atom in successive collisions (two-step process) or in the same collision that produced the electron-positron pair (single-step process). The cross section for the single-step process is negligible because it requires electron capture at the small impact parameters at which the positron is generally produced. Electron capture at small impact parameters is predominately through nonradiative capture (NRC). At 10.8 GeV/nucleon NRC is small for a Au target and negligible for lighter targets [17].

The cross section for the two step process is the product of the probability of capturing an electron in the target times the cross section for free pair production. We set upper limits to the free pair cross section by directly measuring electron-positron pair production without charge change. Combining this with the total capture cross sections from Ref. [16], the background limits are, for 5.0 mg/cm^2 of Au, $\sigma = 0.13$ b; for 4.0 mg/cm^2 of Ag, $\sigma = 0.045$ b; for 10 mg/cm^2 of Cu, $\sigma = 0.047$ b; and for 14.5 mg/cm^2 of Al, $\sigma = 0.016$ b. These limits are included in the total error.

We tested for any target-thickness-dependent systematics (such as count rate effects) by varying the thickness of the Au, Ag, and Cu targets by factors of 5.5, 1.5, and 2.4, respectively. The Au 0.88-mg/cm^2 target gave an 8% *smaller* cross section than the thicker targets, but still within the uncertainties due to target thickness and statistics. All other target thickness variations resulted in cross section changes of less than 3.5%.

V. RESULTS AND COMPARISON WITH THEORY

In Table I we compare our measured cross section for Au^{79+} on a neutral Au target with the calculations for Au^{79+}

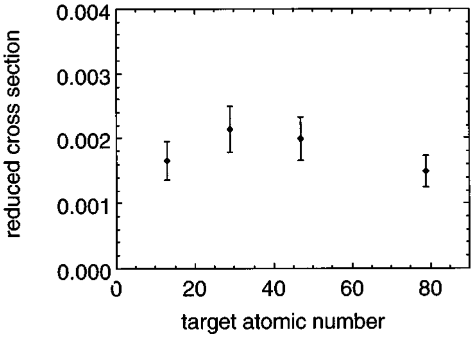

FIG. 2. Measured cross sections divided by Z_t^2 for targets of Al, Cu, Ag, and Au.

ions colliding with bare or one-electron target ions [8,12,15]. (The calculation of Bertulani and Baur [7] for Au projectiles does not extend down to $\gamma = 12$.)

Our measurement is in agreement with the calculation of Becker, Grün, and Scheid [12] for all targets; appears to be in agreement with Rhoades-Brown, Bottcher, and Strayer [8] for a gold target; but is smaller (by about twice our stated error) than that of Baltz, Rhoades-Brown, and Weneser [15] for a Au target. Of these three calculations, Baltz, Rhoades-Brown, and Weneser [6,15] give the smallest cross sections for the RHIC and LHC and the largest cross section for 10.8 GeV/nucleon.

Figure 2 shows the reduced cross sections (measured cross section divided by Z_t^2, where Z_t is the target atomic number) for capture from pair production for targets of Au, Ag, Cu, and Al. A Z_t^2 dependence is predicted by simple perturbation theory if there are no effects from the target electrons. A least-squares fit to the data in Fig. 2 gives a dependence of $Z_t^{1.93}$, but a ''Student's t'' distribution shows that this dependence is in agreement with a Z_t^2 dependence at the 95% confidence level.

The target electrons screen the target nucleus, reducing the effective Z_t, but also act as a low-mass target of Z_t individual particles of charge one. The latter effect increases the cross section by at most $1/Z_t$, which for a gold target is 1.3%. Screening corrections are expected to have only a small effect on the cross section because small impact parameter collisions still dominate in capture from pair production at $\gamma = 12.6$. An extreme upper limit of 20% is obtained by using the screening correction for ionization of Au^{78+} by Au.

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