CAPTURE FROM PAIR PRODUCTION AS A BEAM LOSS MECHANISM FOR HEAVY IONS AT RHIC*

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Abstract

Electron capture from electron-positron pair production is predicted to be a major source of beam loss for the heaviest ions at RHIC. Achieving the highest luminosity thus requires an understanding of the capture process. We report measurements of this process at Brookhaven National Laboratory's AGS using 10.8 GeV/nucleon Au^{79+} projectiles on Au targets. Capture from pair production is a process in which the very high electromagnetic field involved in the collision of two relativistic heavy ions results in the production of an electron-positron pair with the capture of the electron by one of the ions. There are many theoretical papers published on capture from pair production with discrepancies between predicted cross sections. The experimental results are compared to theory and to previous experiments at 1 GeV/nucleon. The implications of extrapolations to RHIC energies are presented.

1 INTRODUCTION

At relativistic energies, the capture of electrons by ions (recombination) occurs by the well-understood collisions processes of Radiative Electron Capture (REC) and Non-Radiative Capture (NRC). These processes, which require an electron in the initial state, have cross sections that decrease rapidly with increasing collision energy. REC is the capture of a target electron by the ion with the simultaneous emission of a photon (to balance momentum and energy). NRC is the capture of an electron that is initially bound to a target atom or ion. Until recently, REC and NRC were thought to be the dominant processes for electron capture at all relativistic energies.

The large transient fields produced in relativistic charged particle atomic collisions (no nuclear contact) have long been known to produce electrons through electron-positron pair production [1]. But, in 1984, Gould pointed out that for bare heavy ions, the probability for pair creation with simultaneous capture of the electron from the pair into the K-shell, was significant [2]. The cross section for this "capture from pair production" mechanism has been shown to increase with energy (as does the cross section for producing free electron-positron pairs), and is predicted to be the dominant electron capture mechanism at highly relativistic energies [3]. Since capture from pair production requires no electron in the initial state, it can take place between two bare ions, possibly limiting the lifetime of stored beams of bare heavy ions in relativistic heavy ion colliders.

A number of theoretical papers aimed at calculating the cross sections for electron capture from pair production have been published since 1984 [4]. Different calculational techniques were used for high and low relativistic factor (γ). Therefore agreement at low energies does not assure agreement at high energies. Until recently, no experimental measurement to check the validity of the theoretical predictions at high γ has existed.

In this article we report measurements of electron capture from electron-positron pair production in relativistic heavy ion collisions at highly relativistic energies, and discuss the possible implications for the lifetime of heavy ions in the Relativistic Heavy Ion Collider (RHIC) now being constructed at Brookhaven National Laboratory [5]. The experiments have been performed at the AGS accelerator at Brookhaven National Laboratory, using 10.8 GeV/nucleon bare gold ions (Au^{79+}) incident on thin, fixed targets of Au, and are compared to experiments at the Bevalac accelerator at Lawrence Berkeley Laboratory, using 0.4 - 1.3 GeV/nucleon bare lanthanum ions (La^{57+}) incident on gold targets.

2 EXPERIMENT DESCRIPTION

Figure 1 shows a diagram of the Advanced Positron Spectrometer (APS) used to detect positrons. The Au^{79+} ion passes through a fixed target located inside the APS, described below. In the case of capture from pair production, the electron is created directly bound to the gold ion, changing its charge by one unit to Au^{78+}. The experimental signature is the detection of the positron emitted during the collision, in coincidence with the charge-changed Au^{78+}. The Au^{78+} is magnetically separated from the main beam of Au^{79+} and each charge state is detected by a scintillator-photomultiplier tube detector.

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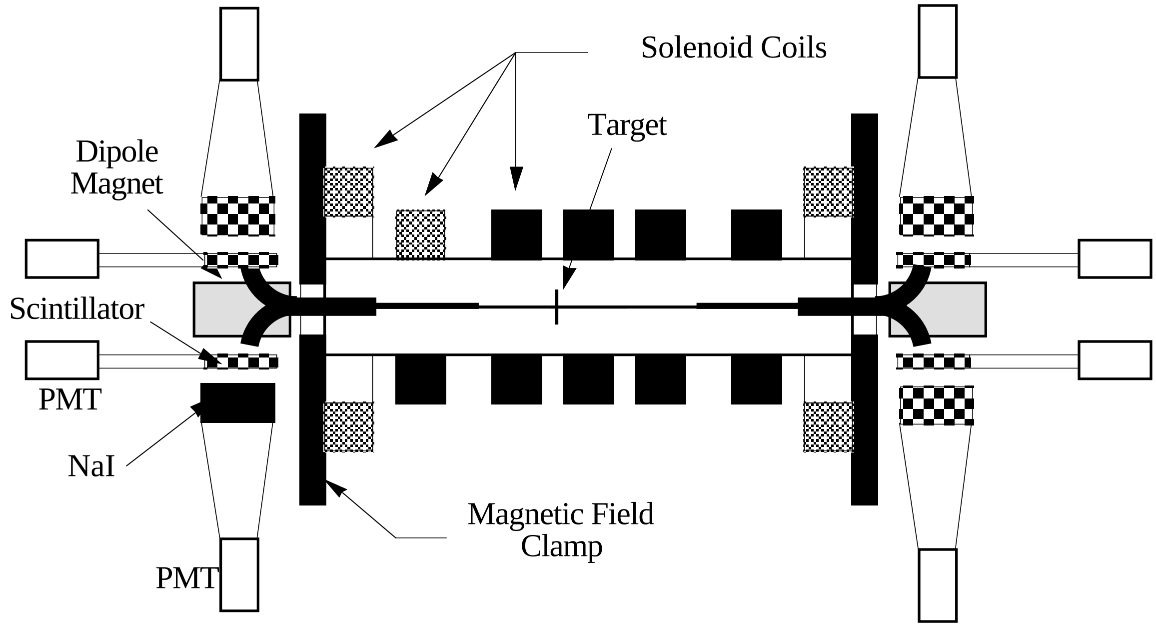

Figure 1 - Schematic diagram of the apparatus (top - sectional view). The solenoid field decreases adiabatically from the center towards the ends causing the particle orbits to grow and their divergence to decrease, allowing them to be swept by the dipole magnets into the detectors. Only one positron detector (and no electron detector) is labeled. The target is located near the center of the solenoid and the heavy ion beam travels horizontally through the apparatus.

The target is placed inside and slightly upstream from the center of the APS. The APS is used to detect and measure the energy distribution and angular distribution of the electrons and positrons emitted from the target. It contains a solenoid magnet in the center and a dipole magnet at each end. The solenoid generates a strong magnetic field (B=0.8 T max.) that adiabatically decreases toward the ends. The field transports the electrons and positrons away from the target, and converts much of the positron (electron) transverse motion into longitudinal motion. The positrons and the electrons are efficiently deflected in opposite transverse directions at each end of the solenoid by the dipoles. There they strike plastic scintillator-photomultiplier tube detectors.

This combination of magnetic fields results in a very high acceptance for electrons and positrons emitted both forward and backward with respect to the beam direction. Without the adiabatically decreasing field, the acceptance of the spectrometer would be very low because most of the positrons, upon reaching the end of the solenoid field, would have a large transverse motion causing them to strike the walls of the apparatus rather than to be deflected into the spectrometer detectors. Tests of the APS using beams and radioactive sources have shown a detection efficiency close to unity for emission angles of up to 75 degrees forward and backward.

The emission angle with respect to the beam direction is measured using the time of flight of the positrons (electrons) through the solenoid. Four plastic scintillator-detectors (see figure 1) are used to detect the positrons (electrons) and to measure their energy and time of flight. The magnetically separated Au^{78+} ion that produced the positron, detected in its scintillator-detector at the end of the beamline, is used for the timing reference.

The dipole magnets that deflect electrons and positrons in opposite directions are used for the initial discrimination between electrons and positrons. However, at 10.8 GeV/nucleon, a large number of knock-on electrons are ejected from the target by collisions with the gold ion. Approximately 3 to 4 electrons with an energy above 100 keV are ejected from a 1 mg/cm^2 gold target for every gold ion, while only one positron from the same target is expected for every 5 x 10^3 gold ions. Roughly two or three per thousand knock-on electrons backscatter from the electron scintillator-detector into the positron scintillator-detector, thus simulating a positron.

To discriminate against these scattered electrons we require the detection of one of the two 511 keV photons that are emitted back-to-back when the positrons annihilate at rest in the plastic scintillator. The 511 keV photon is detected by a NaI scintillator-photomultiplier detector (see figure 1). The detection efficiency of the photon (by the 12.5 cm diameter by 15 cm long active area) NaI detector has been measured to be 30%, with roughly 60% of the photons appearing as a narrow single peak at 511 keV, and the rest as a broad Compton distribution. In our data analysis only the narrow peak is used. This sets the overall efficiency of the APS for the detection of a positron at 18%.

3 RESULTS

We integrate the spectra over the positron energy and angle to obtain the total cross section for capture from pair production. Preliminary results for the total cross section for capture from pair production by a 10.8 GeV/nucleon Au^{79+} on a gold target are 9.2 barns.

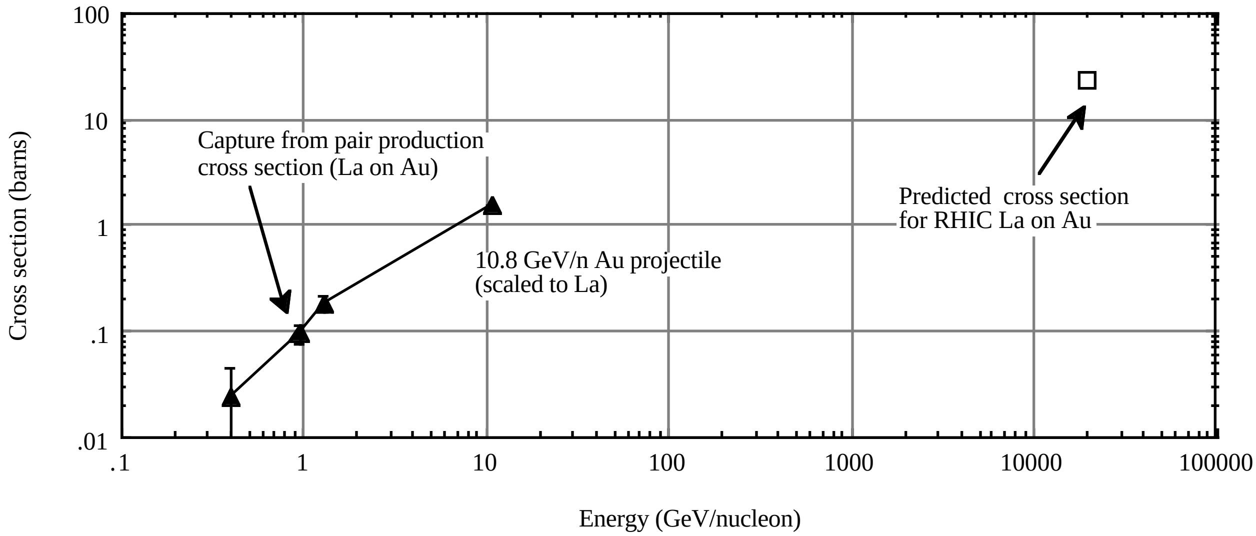

Figure 2 - Graph of capture from pair production as a function of energy. All results are scaled to La on Au, the case for which the most experimental data exists. The triangles represent measured cross sections, while the square point at RHIC energies, scaled to La, is predicted from perturbation theory.

4 DISCUSSION

The preliminary results presented here are in the middle of the range of predictions. These calculations, based on perturbation theory, predict cross sections ranging from 5.7 barns to 12.2 barns [6 - 9].

A convenient way to visualize the cross section for capture from pair production as a function of energy is to scale the collision system to La on Au, where the most experimental results exist [3]. Figure 2 shows the capture from pair production cross section, scaled for a La projectile, as a function of energy. The triangles represent experimental results, scaling the point at 10.8 GeV/nucleon (AGS result) by Z^5 to represent a La projectile rather than a Au projectile. The point for RHIC collider energies is scaled from perturbation theory predictions for Au on Au [10]. A visual analysis of the increase of the experimental cross section with energy indicates that the RHIC predictions are reasonable, but not necessarily assured.

Capture from pair production (resulting in the loss of the charge-changed ion in the collider ring) has been predicted to be the dominant beam loss mechanism for colliding Au + Au beams at RHIC and a significant loss mechanism for lighter ions [5]. If the cross section is an order of magnitude higher than predicted at RHIC energies, then the current after 10 hours will decrease to about 20% of the initial value, instead of 77%, after taking into account intrabeam Coulomb scattering.

Measurements of the cross section for capture from pair production at AGS energies indicate that the high-γ calculations used to predict the loss rate at RHIC are not unreasonable at the low end of their range of validity.

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