Projectile Energy and Atomic Number Dependence of Electron Capture from Pair Production in Relativistic Heavy Ion Collisions

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We report the first measurement of the energy dependence of electron capture from electron-positron pair production in relativistic heavy ion collisions. For a La^{57+} beam incident on Au, Ag, and Cu targets at energies of 0.405, 0.956, and 1.3 GeV/u we find that the cross sections for capture from pair production and the free pair production process increase with increasing collision energy at similar rates. Combining with uranium data reported previously gives a projectile atomic number dependence for 0.956 GeV/u ions on a Au target of $Z_p^{6.54\pm0.65}$ for capture from pair production and $Z_p^{1.53\pm0.80}$ for the free pair production process.

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We report the first experimental evidence that the cross section for electron capture from pair production *increases* with increasing relativistic collision energy—a unique property that distinguishes it from all other known electron-capture mechanisms. Our results support the conclusion that, at higher energies, capture from pair production will become the dominant electron capture mechanism and will contribute to beam loss in relativistic heavy ion colliders [1]. We also report the dependence of the cross section on the atomic number of the ion involved in the collision. 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, with the electron created directly bound to one of the ions [2–8].

The experiment was performed at the Lawrence Berkeley Laboratory's Bevalac, using 0.405, 0.956, and 1.3 GeV/u La^{57+} beams incident on thin gold, silver, and copper foil targets. The experimental setup and apparatus is the same as described in Ref. [2] for a U^{92+} beam. The instantaneous beam intensity typically varied between 3×10^4 and 5×10^6 La^{57+} ions per second on target.

Upon passage through a foil target of thickness between 1.0 and 4.2 mg/cm^2, 0.1% to 0.2% of the incident La^{57+} ions change their charge state to La^{56+} predominantly by the transfer of an electron from the target to the ion. The target thicknesses are chosen to keep the probability of stripping a captured electron to less than 20%. The beam is then charge-state analyzed by large dipole magnets, and each charge state is detected by a plastic scintillator-photomultiplier detector. We use the Advanced Positron Spectrometer to detect the positrons that are created at the target. A description and a brief discussion of the performance of the Advanced Positron Spectrometer can be found in Ref. [2].

The data for all three energies were collected in a single, uninterrupted, 104-h run. The data acquisition system and the electronics, including threshold levels, coincidence windows, and detector gains, were the same for the different energies. To achieve the same trigger timing at different energies, timing delays were added to the beam output signals to compensate for the differences in the time of flight for the different beam energies over the 15-m separation between the positron detectors and the beam detectors.

We first investigate the energy dependence of the total electron-capture cross section by the projectile, regardless of whether an electron-positron pair is created in the collision. For this measurement we determine the fraction of La^{56+} ions formed by the passage of the La^{57+} beam through the foil target. Since only one positron is emitted for every 10^3 or 10^4 charge-change events, this (La^{56+}) fraction is formed predominantly by electron transfer from a target atom to the La^{57+} projectile. The transfer is by a combination of radiative electron capture and nonradiative

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capture. Radiative electron capture is the capture of a target electron by an ion with the simultaneous emission of a photon, and nonradiative capture is the radiationless capture of an electron initially bound to a target atom.

Figure 1 shows the cross section for electron transfer from Au, Ag, and Cu targets to the La^{57+} projectile as a function of the projectile energy. As expected, the cross sections, shown on a logarithmic scale, decrease very rapidly with increasing projectile energy for all targets and are reduced by 1 to 2 orders of magnitude between 0.405 and 1.3 GeV/u. Also, these results, which agree well with previously published data [9], show a very strong dependence on the target atomic number (Z_t). This feature reflects a large contribution from nonradiative capture which varies roughly as Z_t^5. The radiative electron-capture contribution varies linearly with Z_t [7,10].

In the measurement of capture from pair production, we use the detection of a positron in coincidence with the detection of a charge-changed La^{56+} ion as the trigger. Figure 2(a) shows the cross section (divided by Z_t^2) for Au ($Z_t = 79$), Ag ($Z_t = 47$), and Cu ($Z_t = 29$) targets measured for 0.405 GeV/u, 0.956 GeV/u, and 1.3 GeV/u La^{57+} projectiles. The cross sections measured at the low collision energy (0.405 GeV/u) for Ag and Cu targets are very small (smaller than the uncertainty of the measurement). As the projectile energy increases, the cross section for capture from pair production is found to increase; in contrast to the cross section for electron transfer from the target which decreases.

The data in Fig. 2(a) include a contribution from false events corresponding to free electron-positron pair production (pair production without electron capture) in coincidence with the transfer of a target electron to the La^{57+} projectile by nonradiative capture. This background, discussed in detail in Ref. [2], should reflect the Z_t^5 dependence of nonradiative capture combined with the Z_t^2 dependence of free pair production. (By contrast, the Z_t dependence of capture from pair production is much weaker [2].) A strong Z_t dependence is clearly observed for the 0.405 GeV/u projectile energy by contrasting data from the Ag and Au targets. This background cannot be calculated exactly because it is dominated by the double process (free pair production and transfer of a target electron) occurring in the same collision. We estimate that at least two-thirds of the events measured at 0.405 GeV/u for the Au target are false events. If we make the extreme assumption that all the events measured at 0.405 GeV/u for the Au target are false, then an upper limit on the contributions of the false events at 0.956 and 1.3 GeV/u is set at 20% and 10%, respectively, for the Au target.

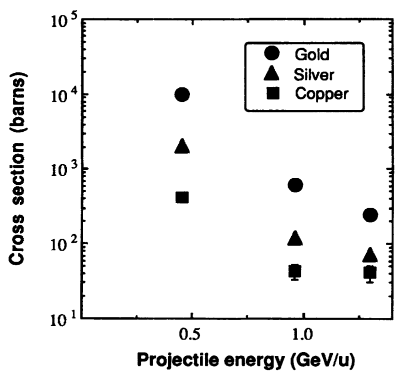

FIG. 1. Total electron capture cross section as a function of energy for La^{57+} ions colliding with Au, Ag, and Cu targets. These cross sections include contributions from radiative electron capture, nonradiative capture, and capture from pair production.

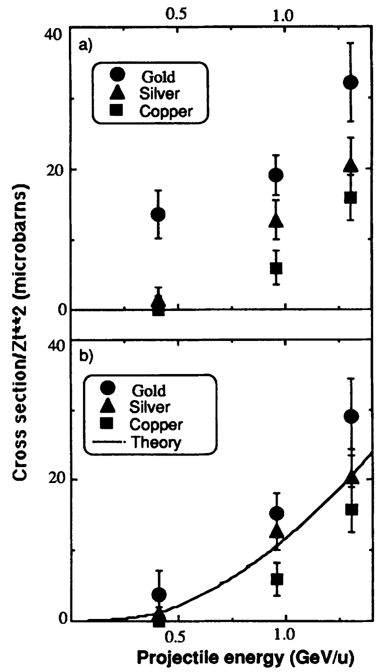

FIG. 2. Cross sections (divided by Z_t^2) for electron capture in coincidence with the detection of a positron for La^{57+} incident on Au, Ag, and Cu targets. (a) These cross sections are a sum of capture from pair production and false events due to free pair production along with the capture of a target electron. (b) Data in (a) corrected for accidental events. Calculations based on first-order perturbation theory are shown as a solid line.

Figure 2(b) shows the capture from pair production cross sections corrected for the background due to the false events. These corrections are negligible for the low-Z targets at all three energies and very small for the high energies, due to their small electron-transfer cross sections (Fig. 1). As a result of this correction, the cross section in Fig. 2(b) for the Au target displays a steeper variation with the projectile energy than in Fig. 2(a).

We also show in Fig. 2(b), the results of a calculation based on first-order perturbation theory [3]. This calculation, which yields a Z_t^2 dependence, includes the contribution of the excited states of the projectile to the total cross sections. We find that, in the energy range studied here, first-order perturbation theory correctly predicts the energy dependence but does not account for a measured target Z_t dependence that is stronger than Z_t^2 ($Z_t^{2.95\pm0.40}$ for 0.956 GeV/u and $Z_t^{2.65\pm0.35}$ for 1.3 GeV/u). For the U^{92+} projectile at 0.956 GeV/u on a Au target, reported in Ref. [2], we found that perturbation theory underestimated the cross section by about a factor of 2.

The results reported in Fig. 2(b) are the first experimental evidences of an electron-capture process having a cross section that increases with increasing relativistic collision energy. If the trend observed here continues, capture from pair production will become the dominant electron-capture mechanism. A calculation based on first-order perturbation theory predicts that, for bare uranium ions on a uranium target, this will take place at about 20 GeV/u [10].

Another important aspect of capture from pair production is the dependence of its cross section on the projectile atomic number (Z_p). (Note that in the experiments reported here the projectile is the ion which picks up the electron created during the collision.) In Ref. [2] we reported a cross section of 2.19 $\pm$ 0.25 b for a 0.956 GeV/u U^{92+} projectile on a Au target. Combining this result with the La^{57+} result, reported here for the same energy, we find a $Z_p^{6.54\pm0.65}$ dependence for the capture from pair production process. A Z_p^5 dependence is predicted by first-order perturbation theory and is also characteristic of nonradiative capture from a target [7]. The large error bars are dominated by the uncertainty due to the contribution of false events discussed above. Note that some systematic errors such as the target thickness and the detector efficiency do not contribute to the total uncertainty on the Z_p dependence.

For comparison to the capture from pair production results we measured the free electron-positron pair production process [10–13] for La^{57+} during the same run at the same energies using the same targets. The signature of free pair production is the detection of a positron emitted in coincidence with a La^{57+} projectile (with no charge change during the collision) striking the beam detector. In Fig. 3, we show the free pair production cross section as a function of the La^{57+} projectile energy for Au, Ag, and Cu targets. Similar to capture from pair production, the cross section for free pair production is found to increase with increasing collision energies. At 1.3 GeV/u, the cross section is about 6 times higher than at 0.405 GeV/u for the Au target. Also shown in Fig. 3 is a perturbation theory calculation of the free pair production cross section as a function of energy [12]. In this case, the perturbation calculation overestimates the measured values at the higher projectile energies.

Continuing our comparison, we find a $Z_p^{1.53\pm0.80}$ dependence for free pair production. As expected, the dependence of the free pair production cross section on Z_p is similar to its dependence on the target atomic number, which from Fig. 3 is $Z_t^{2.65\pm0.35}$ at 0.965 GeV/u and $Z_t^{2.15\pm0.25}$ at 1.3 GeV/u. Since the electron and the positron are created free with respect to the target and projectile, the total cross section should have the same dependence on Z_p and Z_t. In contrast, for capture from pair production, the projectile atomic number dependence is much stronger than the target atomic number dependence reflecting the fact that for larger binding energies, the electron of the pair is more likely to be created in a bound state.

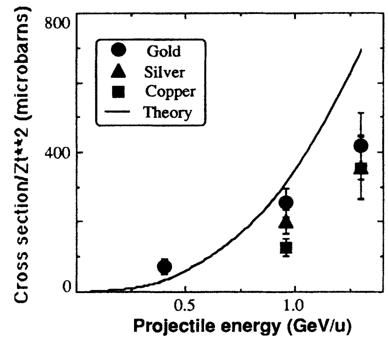

FIG. 3. Free pair production cross section (divided by Z_t^2) for La^{57+} incident on Au, Ag, and Cu targets as a function of the La^{57+} projectile energy. Calculations based on first-order perturbation theory are shown as a solid line.

In summary, capture from pair production has been shown to be the only known electron capture mechanism at relativistic energies where the cross section increases with increasing energy. In the 1 GeV/u energy range its cross section increases at about the same rate as the free pair production cross section. Because of the binding energy effects, capture from pair production displays a much stronger dependence on the projectile atomic number than on the target atomic number.

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[1] H. Gould, Lawrence Berkeley Laboratory Report No. LBL-18593, 1984; see also BNL Report No. BNL-52195, pp. 117–121. See especially Table IV 3–5.
[2] A. Belkacem, H. Gould, B. Feinberg, R. Bossingham, and W. E. Meyerhof, Phys. Rev. Lett. **71**, 1514 (1993).
[3] U. Becker, J. Phys. B **20**, 6563 (1987).
[4] K. Rumrich, K. Momberger, G. Soff, W. Greiner, N. Grün, and W. Scheid, Phys. Rev. Lett. **66**, 2613 (1991).
[5] G.R. Deco and R.D. Rivarola, J. Phys. B **21**, 1229 (1988).
[6] M.J. Rhoades-Brown, C. Bottcher, and M.R. Strayer, Phys. Rev. A **40**, 2831 (1989).
[7] R. Anholt and U. Becker, Phys. Rev. A **36**, 4628 (1987).
[8] A.J. Baltz, M.J. Rhoades-Brown, and J. Weneser, Phys. Rev. A **44**, 5569 (1991).
[9] R. Anholt, W.E. Meyerhof, X.-Y. Xu, H. Gould, B. Feinberg, R.J. McDonald, H.E. Wegner, and P. Thieberger, Phys. Rev. A **36**, 1586 (1987); W.E. Meyerhof, R. Anholt, J. Eichler, H. Gould, Ch. Munger, J. Alonso, P. Thieberger, and H.E. Wegner, Phys. Rev. A **32**, 3291 (1985).
[10] J. Eichler, Phys. Rep. **193**, 165 (1990).
[11] C.A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988).
[12] U. Becker, N. Grün, and W. Scheid, J. Phys. B **19**, 1347 (1986).
[13] C.R. Vane, S. Datz, P.F. Dittner, H.F. Krause, C. Bottcher, M. Strayer, R. Schuch, H. Gao, and R. Hutton, Phys. Rev. Lett. **69**, 1911 (1992).