Ionization of Au^{78+} and electron capture by Au^{79+} at 10.8 GeV/nucleon

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We have measured the cross sections for ionizating one-electron Au^{78+} and the total cross sections for electron capture by bare Au^{79+} at 10.8 GeV/nucleon in C, Al, Cu, Ag, and Au targets. We made the measurement by magnetically separating the charge states and measuring the fraction of Au^{78+} as a function of target thickness for each element. In contrast to the results reported by Westphal and He [Phys. Rev. Lett. **71**, 1160 (1993)], our ionization measurements agree with the calculation of Anholt and Becker [Phys. Rev. A **36**, 4628 (1987)]. Our capture cross-section measurements are in agreement with theory for those targets where radiative electron capture is the dominant capture process. [S1050-2947(97)50402-1]

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Recently Westphal and He [1] have reported a measurement of the cross section for ionizating one-electron Au^{78+} at an energy of 10.8 GeV/nucleon. Their measured ionization cross section, the first for heavy ions in the energy range above 1 GeV/nucleon, is one-half the cross section calculated by Anholt and Becker [2]. This is surprising because effects that can lead to discrepancies between ionization theory and measurement are expected to decrease with increasing collision energy [3]. Furthermore, at lower energies, ionization theory, when not in agreement with measured cross section generally underestimates the cross section [4].

To resolve this disagreement we measured the ionization cross section for Au^{78+} (one-electron Au) at 10.8 GeV/nucleon in C ($Z_t=6$), Al ($Z_t=13$), Cu ($Z_t=29$), Ag ($Z_t=47$), and Au ($Z_t=79$) targets. We used magnetic separation to analyze the Au^{78+} and Au^{79+} charge states emerging from the targets, and determined the Au^{78+} ionization cross sections and the Au^{79+} capture cross sections by measuring the fraction of Au^{78+} as a function of target thickness for each element (Z_t). This direct and traditional method has been reliably used for similar measurements at lower energies [4]. By comparison, Westphal and He measured mean free paths of Au^{78+} (and Au^{79+}) ions, using barium phosphate glass as target and detector [1]. Both experiments were performed at the Brookhaven National Laboratory's alternating gradient synchrotron (AGS) accelerator. The energy of 10.8 GeV/nucleon corresponds to a Lorentz factor γ of 12.6.

We performed our measurement in two complementary ways. In the first, we passed a beam of pure Au^{79+} through a target and measured the fraction of Au^{78+} as a function of target thickness. These data are shown for aluminum targets in the lower curve of Fig. 1. The data were analyzed using the method described by Betz [5], which is very simple for a system where, due to the small size of the capture cross sections, only two charge states (Au^{78+} and Au^{79+}) need to be considered. We obtained cross sections for ionization of Au^{78+} and capture by Au^{79+} by fitting the data for each target element with

$$f_{78}=\sigma_c/(\sigma_c+\sigma_i)[1-e^{-(\sigma_c+\sigma_i)x}], \tag{1}$$

where f_{78} is the fraction of Au^{78+} ions, σ_c is the total capture cross section in barns, σ_i is the ionization cross section in barns, and x is the target thickness in atoms/barn. In this method, the capture cross section is determined primarily by the thin target data, and the ratio of the capture cross section to the ionization cross section is determined by the equilibrium fraction of Au^{78+} in the thickest targets. The equilibrium fraction of Au^{78+} ranged from 6×10^{-3} for a 356-mg/cm^2 carbon target to 6.5×10^{-4} for a 46-mg/cm^2 gold target.

An incident beam of pure Au^{79+} was assured by transporting the ions through a beamline with a windowless 20.5° bend upstream of our apparatus, and by maintaining the portion of the beamline after the bend under high vacuum. The separated charge states (9-mm separation at a

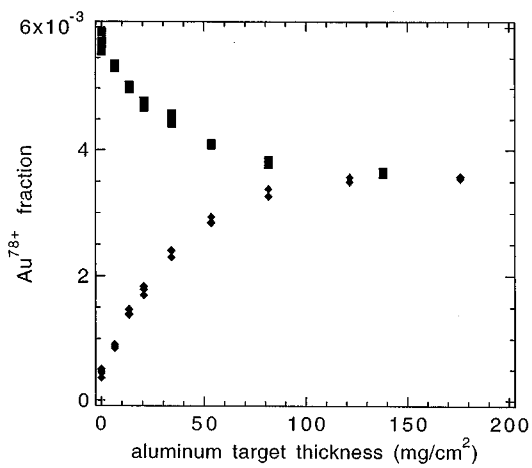

FIG. 1. Fraction of Au^{78+} as a function of aluminum target thickness. The lower graph shows the fraction of Au^{78+} from a beam of initially pure Au^{79+}. The upper graph shows the fraction of Au^{78} from a beam initially of 0.58% Au^{78+} (and 99.42% Au^{79+}).

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TABLE I. Cross sections for 10.8-GeV/nucleon Au.

	Ionization of Au^{78+}		Electron capture by Au^{79+}	
Z_t	Experiment (barns)	Theory [a] (barns)	Experiment (barns)	Theory [b] (barns)
6	310.0 (30)	310.0	1.8 (0.20)	1.62
13	1180.0 (90)	1280.0	3.9 (0.40)	3.67
29	5260.0 (500)	5800.0	7.2 (1.1)	9.0
47	162.00.0 (1400)	14400.0	16.1 (1.5)	16.8
79	38200.0 (3200)	38800.0	28.6 (3.0)	43.3

[a]Reference [2].
[b]References [8–14]; see text.

horizontal focus of 1–2 mm) were detected by scintillator-photomultiplier tube detectors arranged vertically to keep the phototubes and light guides out of any spray of beam fragments. The spillover of Au^{79+} onto the Au^{78+} detector, determined by measuring the apparent Au^{78+} yield with no target, depended upon the width of the scintillator and the quality of the beam tune, and ranged from 1×10^{-4} to 5×10^{-4} of the Au^{79+}. This background was accounted for in our data analysis.

A beam is extracted from the AGS by changing its momentum by roughly 0.5%. This can sweep the position of the beam many centimeters. The change in momentum of the beam over the approximately one second spill was partially compensated for by ramping the magnetic field of several of the bending magnets in our beam line. In addition, by the proper choice of location and focal length of focusing magnets in our beamline, we were able to obtain a horizontal focus at our detectors and a horizontal and vertical focus near the targets, with zero dispersion at both of these locations relative to the exit of the AGS. This combination of magnet ramping and beam optics made our experiment insensitive to changes in the beam momentum.

In the second method we placed a 184-mg/cm^2-thick carbon target in the Au^{79+} beam to produce a beam of approximately 0.6% Au^{78+} and 99.4% Au^{79+}. Then, using additional, higher Z_t targets, we measured the fraction of Au^{78+} as a function of target thickness for Al, Cu, Ag, and Au. Data taken using this method are shown for aluminum targets in the upper curve of Fig. 1. In this complementary measurement, the Au^{78+} ionization cross section is determined primarily by the thin target data, and the ratio of the capture cross section to the ionization cross section is determined by the equilibrium fraction of Au^{78+} in the thickest targets. These data were also analyzed using the method described by Betz [5], which gives a slightly different result for the Au^{78+} fraction when the incident beam contains both Au^{78+} and Au^{79+}. We obtained cross sections for ionization of Au^{78+} and capture by Au^{79+} by fitting the data for each target element with

$$f_{78}=\sigma_c/(\sigma_c+\sigma_i)[1-e^{-(\sigma_c+\sigma_i)x}]+\delta e^{-(\sigma_c+\sigma_i)x}, \quad (2)$$

where δ is the incident fraction of Au^{78+} and the other symbols are as before. The two methods give the same cross sections (for Al, Cu, Ag, and Au targets) to within our stated uncertainties in Table I. The combined uncertainties include 7% from the uncertainty in the measured target thickness and the uncertainty from the fitting of the cross sections to the data.

The target thicknesses were measured by weighing or, for the thick targets, by mechanical measurement. In addition, the thin targets were also measured by comparing the energy loss of 5.8 MeV α particles from a Cf^{249} source with energy-loss tables [6].

Our results for ionization, shown in Table I and Fig. 1, agree with Anholt and Becker [2] for every target element measured, and therefore will also agree with theory for any combination of target elements (in the range of $Z_t=6$ to $Z_t=78$). Theory includes a small correction for the screening of the target nucleus by the target electrons. For 10.8 GeV/nucleon Au, the screening correction scales roughly as $Z_t^{1/2}$ and reaches 21% for $Z_t=79$. Figure 2 shows the theory with and without the screening correction. Our data support a screening correction of this size and Z_t dependence.

Results for the total cross section for electron capture by Au^{79+} are shown in Table I and Fig. 3. Three processes contribute to the total cross section: radiative electron capture (REC), nonradiative capture (NRC), and capture from pair production [3]. REC is the capture of a target electron by an ion with the simultaneous emission of a photon. NRC

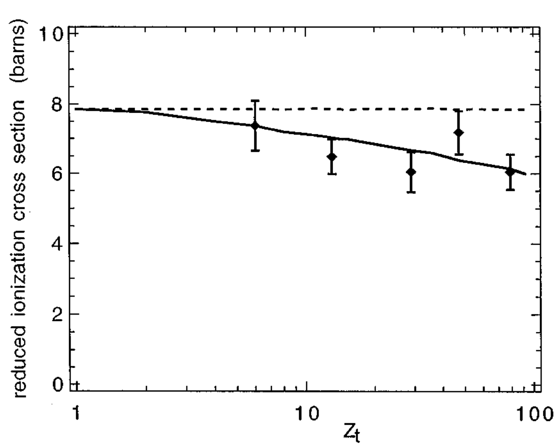

FIG. 2. Measured Au^{78+} ionization cross section (points) compared to theory. The (lower) solid line is theory with screening corrections; the (upper) broken line is theory without screening corrections. The cross sections have been divided by $Z_t^2+Z_t$. The factor of Z_t arises from ionization of the projectile by target electrons.

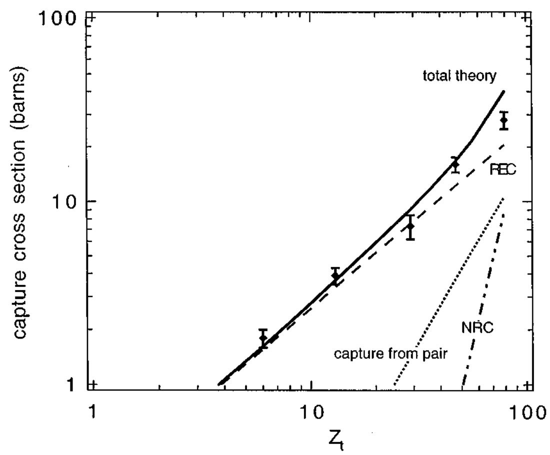

FIG. 3. Measured total Au^{79+} capture cross section (points) compared to the sum (solid line) of radiative electron capture (dashed line), capture from pair production (dotted line), and nonradiative electron capture (chain line).

is the radiationless capture of an electron initially bound to a target atom, with momentum and energy being conserved by changes in the motion of the target and projectile. Capture from pair production 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 [7].

Figure 3 compares our measured total cross sections with theory. REC differs only slightly from radiative recombination (in that in REC the electron is initially bound). Since radiative recombination is the inverse of the photoelectric effect, values of REC (which scale as Z_t) can be obtained from the photoelectric cross section σ_ϕ by the relation [8]

$$\sigma_{\mathrm{REC/electron}}=[(\gamma-1)+B_n]^2\sigma_\phi/(\gamma^2-1), \tag{3}$$

where B_n is the binding energy of the nth shell in units of the electron rest mass, and is in this situation small compared to $\gamma-1$. The photoelectric cross section for Au at 6.0 MeV (the energy of the electron seen in the rest frame of the Au projectile) is taken from Hubbell [9]: Identical values for the REC cross section are obtained using values for REC into the Au K shell, obtained from Ref. [10] and adding 20% to account for capture into the higher shells.

The NRC cross sections, for Au^{79+} (on hydrogenlike ions), which scale roughly as Z_t^5 are taken from the tables of Ichihara *et al.* [11] and scaled from 10-GeV/nucleon to 10.8-GeV/nucleon using the formulas of Eichler [12]. The capture from the pair-production cross section at 10.8 GeV/nucleon is assumed to scale as Z_t^2 and we use a theoretical cross section of 10.6 barns for a Au target. This is an average of the values calculated in Refs. [13] and [14].

Theory and experiment show that for Au^{79+} at 10.8 GeV/nucleon Au, REC is the dominant capture process for all but the highest Z_t target elements, and our experiment is in good agreement with theory in the region where REC is the dominant capture process. A possible disagreement with theory is seen for capture from a gold target where NRC and capture from pair production are significant. Analysis of a separate experiment, which measures capture from pair production, is underway.

In conclusion, we have measured the ionization cross section for Au^{78+} and capture cross sections for Au^{79+} at 10.8 GeV/nucleon. In contrast to Westphal and He [1], our ionization cross sections all agree with the calculation of Anholt and Becker [2]. We have shown that capture theory is in good agreement with experiment in the region where REC is the dominant capture mechanism.

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