PRODUCTION OF HIGH-Q IONS BY LASER BOMBARDMENT METHOD

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Summary

The expanding plasma produced when an intense pulse of laser radiation is focused in vacuum onto a solid target has been used as a source of highly stripped ions for collision cross-section measurements. Usable fluxes of carbon nuclei at energies of a few hundred eV/charge have been obtained by irradiation of graphite with pulses of CO_2 laser radiation at a focused power density of $3 \times 10^{10} \text{ W/cm}^2$. Bombardment of aluminum and iron targets at comparable power levels have yielded ions of maximum charges of 9 and 16 respectively. A time-of-flight apparatus has been constructed to utilize the laser source for measurement of electron capture cross sections for highly stripped ions in gases at energies in the few hundred eV/charge range. Apertures collimate an ion beam from the plasma blowoff, and an electrostatic analyzer selects ions from the expanding plasma which have the same energy per charge. The beam is directed through a gas target cell, charge analyzed once more by deceleration, and detected by a channel plate electron multiplier used in a current amplification mode. Electron capture cross sections have been measured for C^{+q} ions, $q = 3, 4, 5$ in H_2 at energies ranging from 150–1160 eV/charge. Preliminary data have been obtained for carbon ions in atomic hydrogen, and similar measurements are planned for O^{+q} and Fe^{+q} ions.

Introduction

During the last decade, considerable experimental and theoretical effort has been directed toward the characterization of laser-produced plasmas,¹⁻³ and the basic physics of the interaction between intense laser light and matter is now much better understood. The utilization of such an expanding plasma as a source of highly stripped ions for the quantitative study of atomic collision processes has apparently been limited to a single experiment reported by Goldhar, Mariella, and Javan⁴ in 1976. They measured cross sections for single and double electron capture in noble gases by highly stripped carbon ions from a laser-produced plasma.

At collision velocities below 10^8 cm/s , electron capture cross sections for multiply charged ions are generally large (up to 10^{-14} cm^2) and thus play an important role in physical systems in which they occur. In the photon-ionized interstellar medium, charge exchange in low velocity collisions with hydrogen and helium is important in reducing degree of ionization of multicharged ions.⁵ In addition, charge-changing collisions between highly ionized impurities and hydrogen influence the impurity transport in magnetically confined fusion plasmas and the interpretation of diagnostic measurements.^{6,7} Such collisions

Figure 1. Pulsed-laser ion source and time-of-flight electron capture collision apparatus.

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have generally proven difficult to treat theoretically, since a quasi-molecular description of the collision process is required at low velocities.⁸ Thus, a few definitive cross-section measurements on nearly or fully stripped ions colliding with simple atoms are needed for testing theoretical models of electron capture.

Experimental Method

The arrangement of the time-of-flight apparatus used in these experiments is similar to that used by Goldhar and co-workers⁴ and is shown in Fig. 1.

1. Laser and Optical System

A 2-3 J pulse of 10.6 μ radiation 60 ns in duration from a commercial TEA-CO₂ laser is directed into a vacuum chamber and focused by a 15-cm focal length spherical mirror to a spot of dimension 0.6 mm x 0.3 mm on a solid target. The resulting laser power density is $(2-3) \times 10^{10}$ W/cm² at the target. The laser can be operated at a repetition rate of up to 1 Hz. Approximately 4% of the laser light is reflected by the NaCl vacuum window and is focused onto a Ge photon drag detector to provide a timing pulse. The laser was operated with an unstable resonator front optic, which constrained operation to fundamental mode. This modification shortened the gain-switched spike from 150 ns to 60 ns and reduced beam divergence from 3.5 to 0.6 mrad, providing an increase in focused power density of more than an order of magnitude.

2. Ion Beam Transport

A series of apertures nominally 3-mm diam collimate a beam from the plasma blowoff normal to the target. A fine 100 mesh wire grid located 10 cm before the analyzer entrance aperture serves to separate the electrons from the ions in the plasma beam. The cylindrical electrostatic analyzer has a radius of curvature of 78 cm and electrode spacing of 3 cm. The energy spread of the transmitted beam was typically 2-3%, depending on the size and placement of the beam-defining apertures. Ions from the expanding plasma with energy per charge selected by the analyzer were directed through a differentially pumped collision cell 5 cm long with entrance and exit apertures 0.1 and 0.2 cm in diam respectively. The beam then passed through a gridded deceleration tube 28 cm long and was detected by a channel electron multiplier array (CEMA) detector having a 2.5-cm aperture. A set of three coils surrounding the deceleration tube produced a variable axial magnetic field of up to 0.02 T, which serves to collimate the ion beam, offsetting the ion beam blowup in the deceleration tube. The total path length from the laser target to the CEMA detector is 260 cm.

3. Collision Cell Calibration

Gas was metered into the collision cell all through a small capillary tube of known conductance. Measurement of the pressure differential across this tube with a capacitance manometer gave a direct determination of the gas flow into the collision cell. The gas density in the cell was then determined from the gas flow and the known conductances of its apertures. End corrections to the target thickness were kept to 3% by the large ratio of cell length to aperture diameter. This arrangement was used for most of the C⁴⁺ + H₂ electron capture measurements and was subsequently replaced by the ORNL atomic hydrogen target,⁹ which was modified and recalibrated for these experiments, using a probe beam of 20-keV H⁺ ions.⁹ Cross-section measurements made for C⁴⁺ + H₂ collisions ($q = 4, 5$) using the two collision cells are in excellent agreement.

4. Time-of-Flight Analysis

The separation of the various ion charges by time of flight is based on the fact that the plasma is short-lived relative to ion flight times in the apparatus and that an electrostatic energy analyzer transmits ions of fixed energy per charge. Hence for a given analyzer setting, each charge q will arrive at the detector at a different time t , such that $t = (m/q)^{1/2}$. The deceleration charge exchange analyzer takes advantage of the fact that ions of a selected energy per charge which subsequently capture one or more electrons have increased energy per charge and thus are affected less by electrostatic deceleration than those whose charge has not changed.

5. Ion Detector

Several characteristics of the chevron CEMA detector made it desirable in the present application. The large active area (2.5-cm diam) permitted the entire ion beam to be collected despite significant beam blowup in the deceleration tube. The application of an axial magnetic field to compensate this blowup had no measurable effect on the detector response. The pulsed nature of the laser source resulted in typical fluxes of several hundred ions in 0.5 μ s. Thus, the CEMA was used in a current amplification rather than a pulse-counting mode and, provided the gain was kept below 10^6 , the response was determined to be linear even at these large instantaneous particle arrival rates. This is presumably due to the multipore construction of the detector, its finite capacitance, and the large extent of the impinging beam relative to pore size (12 μ). A fine 982 transmitting grid was placed in front of the CEMA, and the grid and CEMA front were operated at the same negative voltage in order to accelerate the ions and increase the sensitivity for the low energy ions. The grid serves to make the response uniform across the CEMA surface. Detector ion impact energies were in the 8- to 12-keV range, where the mechanism for secondary electron ejection is kinetic rather than potential in nature, and the dependence on ionic charge is expected to be small.¹⁰ The detector bias was arranged such that the potential on the front face could be varied, while the gain was held constant. A linear variation of sensitivity with impact energy was found for C ions ($q = 2, 3, 4, 5$) over the energy range 4-14 keV, the variation being independent of charge. These measurements were used to correct the measured charge exchange ion fluxes, since these ions were accelerated less strongly at the CEMA face and impacted the CEMA at lower velocity than the primary ions.

6. Data Acquisition

The time-of-flight ion signals from the CEMA collector were recorded by a 1024 channel transient digitizer having a resolution of eight bits at 50 ns/channel. A microprocessor controlled the firing of the laser and averaged successive digitized time-of-flight spectra. A typical measurement involved an average of over 50 laser shots at a repetition rate of 0.2 Hz.

Ion Charge and Energy Distributions

A time-of-flight spectrum taken with a laser power density of 3×10^{10} W/cm² on an iron target is shown in Fig. 2. The analyzer setting corresponds to an ion energy of 387 eV/charge and an energy spread of 2% FWHM. The intensities of the various charge states have not been corrected for relative detector response due to varying impact energy. This would increase the lower q peaks relative to those at

higher q roughly in proportion to the ratios of their charges. The smaller peaks which precede or follow the larger ones are due to the 6% and 2% natural abundances of the isotopes ^{54}Fe and ^{57}Fe in the iron target. Simultaneous measurement of the flight time over a known path gives an unambiguous determination of mass/charge. Additional peaks in the 35- to 45- μs range are due to target surface impurities whose relative intensity decreases with successive laser shots on the same spot. The abrupt cutoff at charge 16 reflects the fact that the ionization energy of Fe^{15+} is 489 eV and jumps to 1266 eV for Ne-like Fe^{16+} .

Figure 2. Digitized time-of-flight ion intensity spectrum taken for a laser power density of $\sim 3 \times 10^{10} \text{ W/cm}^2$ on an iron target. Numbers denote the ionic charge. Spectrum represents an average over 50 laser shots and is uncorrected for variation of detector sensitivity with ionic charge.

The intensity variation of the various charge states with ion energy can be determined by measuring spectra like those of Fig. 2 at different analyzer settings. Such a distribution is plotted in Fig. 3 for a graphite target at $3 \times 10^{10} \text{ W/cm}^2$. These data have been corrected for relative detector response. The absolute scale is determined by in situ measurements of the CEHA gain and assuming a value of $\gamma = 6$ for the detector secondary emission coefficient for 10-keV C^{4+} ions, after measurements of Cano¹¹ for gas-covered Au, Mo, and BeCu surfaces. The pressures along the flight path are maintained in the 10^{-7} Torr range, so that charge exchange with residual gas has a negligible effect on the observed distributions.

At a laser power density of $3 \times 10^{10} \text{ W/cm}^2$, the relative intensities of the ionic charge states of both carbon and iron are comparable to a plasma in Boltzmann equilibrium at an electron temperature in the 100- to 150-eV range. In addition to the "thermalized" plasma ions in the 0.2- to 3-keV range, the peaks in the distributions for C^{5+} at 10 keV, C^{4+} at 8 keV, and perhaps, C^{3+} at 7 keV are suggestive of the onset of "superthermal" ion production,^{1,2} where ions behave as though accelerated by a constant potential during the laser pulse.

Figure 3. Variation of ion beam intensity with energy for the various charge states of carbon. Laser power density $\sim 3 \times 10^{10} \text{ W/cm}^2$ on graphite. Points on the graph are represented by numbers which designate the ionic charge. Intensities have been corrected for relative detector response.

Cross-Section Measurements

Time-of-flight spectra illustrating the technique for measurement of electron capture cross sections are shown in Fig. 4 for collisions of 278 eV/charge carbon ions with atomic hydrogen. In this case, the primary ions are delayed about 2 μs in the deceleration tube, and the ions which arrive just prior to the primary ions when gas is admitted into the collision cell have captured an electron and are delayed less in the deceleration tube. The electron capture from the gas in the target cell alone is isolated by making a background measurement with an equal amount of gas admitted into the vacuum system, bypassing the collision cell, as in the upper trace of Fig. 4. The signal-to-background ratio is kept near ten by adequate differential pumping of the collision cell, keeping ambient pressures in the 10^{-7} Torr range. The electron capture fraction is measured as a function of cell gas density. Under single collision conditions, the variation is linear, and the slope is proportional to the capture cross section. The range of gain over which the CEHA detector response is linear is verified by measuring the apparent cross sections at different gain levels.

Experimental electron capture cross sections for C^{+q} ions ($q = 3, 4, 5$) colliding with H_2 are plotted vs ion velocity in Fig. 5. Present measurements are shown, along with data taken at ORNL at higher velocities using other sources of multicharged ions.^{9,12,13} It is significant that C^{4+} has the largest cross sections at these low velocities, counterindicating a simple scaling with ionic charge, as is characteristic of higher velocity collisions.⁹ The cross sections also all increase with decreasing velocity.

Corresponding measurements with an atomic hydrogen target are underway and will provide data for comparison with theoretical calculations.⁸ Similar measurements are planned for ions of O and Fe.

Figure 4. Time-of-flight spectra for carbon ions at 278 eV/charge, with +190 V on deceleration charge analyzer. Ions which have captured an electron are delayed less than the primary ions. Particle density in the atomic hydrogen collision cell is $8 \times 10^{12} \text{ cm}^{-3}$. Spectra are averages over 50 laser shots.

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Figure 5. Experimental electron capture cross sections vs ion velocity for C^{4+} ions in N_2 . Points with flags at lowest velocities are present measurements. Circled points are from Ref. 9, and solid points without flags are data of Crandall et al. (Refs. 12 and 13).

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