Laser and Particle Beams (2002), *20*, 551–554. Printed in the USA.
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DOI: 10.1017/S0263034602204036

Multiple electron stripping of heavy ion beams

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(RECEIVED 26 May 2002; ACCEPTED 24 October 2002)

Abstract

One approach being explored as a route to practical fusion energy uses heavy ion beams focused on an indirect drive target. Such beams will lose electrons while passing through background gas in the target chamber, and therefore it is necessary to assess the rate at which the charge state of the incident beam evolves on the way to the target. Accelerators designed primarily for nuclear physics or high energy physics experiments utilize ion sources that generate highly stripped ions in order to achieve high energies economically. As a result, accelerators capable of producing heavy ion beams of 10 to 40 MeV/amu with charge state 1 currently do not exist. Hence, the stripping cross sections used to model the performance of heavy ion fusion driver beams have, up to now, been based on theoretical calculations. We have investigated experimentally the stripping of 3.4 MeV/amu Kr^{+7} and Xe^{+11} in N_2; 10.2 MeV/amu Ar^{+6} in He, N_2, Ar, and Xe; 19 MeV/amu Ar^{+8} in He, N_2, Ar, and Xe; 30 MeV He^{+1} in He, N_2, Ar, and Xe; and 38 MeV/amu N^{+6} in He, N_2, Ar, and Xe. The results of these measurements are compared with the theoretical calculations to assess their applicability over a wide range of parameters.

Keywords: Inertial fusion; Cross-sections; Heavy ion; Electron

1. INTRODUCTION

Use of energetic heavy ion beams as a driver for inertial confinement fusion is a technique that is under development. The heavy ion beam focused on an indirect drive target would produce X rays, which then compress the deuterium–tritium target (Bangerter, 1996). The target chamber gas in one reference design, HYLIFE-II, would probably be comprised of vapor from FLIBE, a salt of fluorine, lithium, and beryllium. The gas density of beryllium difluoride in this design is expected to be 5×10^{13} cm^{-3} (Callahan, 1996). As the heavy ion beam propagates through this background gas, it would undergo electron stripping reactions that would raise the space-charge density of the beam. This can cause the beam spot to expand, reducing the power density on the target. Ionization of the background gas would supply space-charge-neutralizing electrons, which could compensate for the space-charge defocusing force on the positive ion beam. It is important to have accurate cross sections for electron stripping cross sections of the heavy ion beams in order to estimate these effects on the transport of the beam through the chamber to the target. In a previous experiment using Kr^{+7} and Xe^{+11} beams at 3.4 MeV/amu, the first experimental demonstration that such energetic ions undergo multiple electron stripping events in a background gas of N_2 was made (Mueller *et al.*, 2001). As a result, the charge state of the ion beam increases more rapidly than would be the case if only a single electron were lost in each encounter. This effect must be included in the transport calculations of heavy ion beams. Unfortunately, there are currently no accelerators capable of accelerating heavy ions ($A \sim 200$) with charge state 1 to the energy range envisioned (20 to 40 MeV/amu), so the electron stripping cross sections cannot be measured directly by experiment and must be obtained from theoretical calculations. We have performed additional measurements, which along with those made by Olson *et al.* (2002), provide experimental data for comparison with theory over a range of beam energy, beam species, and gas target species. Agreement of calculations with the measurements would provide a measure of confidence that the theory might be applicable in a regime that is not yet experimentally available.

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2. EXPERIMENT

Beams of 10.2 MeV/amu Ar^{+6}, 19 MeV/amu Ar^{+8}, 30 MeV/amu He^{+1}, and 38 MeV/amu N^{+6} were extracted from the Texas A&M K500 superconducting cyclotron. The beams were directed through a 22° deflection magnet located 10 m in front of the target chamber. The beam was collimated by three 1-mm-diameter apertures followed by a 2-mm-diameter collimator before entering a differentially pumped gas cell. The number of collimators was reduced for the most energetic beams because the range of the beams was greater than the collimator's thickness, and the extra collimators resulted in a large low energy tail on the beam distribution. The gas cell of effective length 0.0208 m was filled with gas (He, N_2, Ar, or Xe) to pressures from 1 to 250 mTorr, as measured by a capacitance manometer, and maintained by an automatic fill valve to about ±0.3 mTorr accuracy. The background pressure in the beam line and target chamber were monitored with ion gauges and ranged between 1.5 and 5.0×10^{-6} Torr, depending on target cell pressure and vacuum history. After exiting the gas cell, the beam passed between the poles of another magnet to disperse the charge states and on to a position-sensitive microchannel plate detector (PSD). Data were also taken with no flow in the gas cell to assess the stripping of the beam in the background gas and scattering from beam collimators. To avoid rate-dependent gain changes and extraneous peaks due to pulse pile-up, the counting rate was kept below 1500 counts/s. The charge distributions were measured until the statistical uncertainties of the number of counts in the peaks representing less than four-electron loss were better than 2%.

3. RESULTS

Tables 1 through 3 list the cross sections for electron stripping of the incident beams in the various target gases. The statistical uncertainty is listed in the tables for each case. There is also an estimated error of about 20% for cross sections below 10^{-18} cm^2 and 10% for cross sections above that, due to differences in assessing the background for each of the peaks in the measured beam charge distribution and in the effective length of the target cell. It is clear that the average number of electrons lost per encounter increases with increasing target atomic number. This effect is most pronounced for 19 MeV Ar^{+8} where the average charge change per encounter rises from 1.16 for He to 2.01 for Xe. The weighted cross sections shown in Table 3 are the cross sections weighted by the number of electrons lost in the encounter. Figures 1 and 2 show the cross section versus number of electrons lost in the various gases by 10.2 MeV/amu Ar^{+6} and 19 MeV/amu Ar^{+8}, respectively. The weighted cross sections for all of the beams we have used so far are summarized in Figure 3 as a function of target atomic number. The cross sections increase with increasing target Z and decrease with increasing beam energy in a broad energy and beam species range.

The cross sections, labeled "Born" and "Classical" in Table 3, are the results of calculations described by Kaganovich *et al.* (2001). The Born approximation, which results in overestimates of the cross sections, should be valid for $Z_T e^2 \ll \hbar V$, where Z_T is the target atomic number and V is the velocity of the beam ion relative to the target atom. The classical trajectory calculations do not account for tunneling transitions allowed by quantum mechanics. Neither approach is expected to perform well across a wide spectrum of beams and targets. Aspects of one must be included in the other to address shortcomings in the underlying assumptions. In the calculations for argon, we used simplistic assumptions based on one-electron ion scaling and ionization

Table 1. *The measured cross sections per atom for electron stripping of 10.2 MeV/amu Ar^{+6} in various gases in units of 10^{-18} cm^2*

Target gas	1*e*	2*e*	3*e*	4*e*	5*e*
He	2.18 ± 0.09	1.65 ± 0.05	0.044 ± 0.02		
N_2	10.77 ± 0.05	8.96 ± 0.03	1.10 ± 0.01	0.221 ± 0.006	0.047 ± 0.003
Ar	27.4 ± 0.2	19.5 ± 0.1	6.17 ± 0.08	2.64 ± 0.04	1.02 ± 0.03
Xe	50.1 ± 0.5	33.1 ± 0.3	13.4 ± 0.2	7.8 ± 0.1	5.6 ± 0.1

Table 2. *The measured cross sections per atom for electron stripping of 19 MeV/amu Ar^{+8} in various gases in units of 10^{-18} cm^2*

Target gas	1*e*	2*e*	3*e*	4*e*	5*e*
He	1.2 ± 0.1	0.12 ± 0.01	0.05 ± 0.01		
N_2	6.33 ± 0.04	0.57 ± 0.01	0.10 ± 0.01	0.030 ± 0.003	0.02 ± 0.01
Ar	16.3 ± 0.1	4.29 ± 0.05	1.50 ± 0.03	0.59 ± 0.02	0.27 ± 0.02
Xe	22.8 ± 0.2	9.86 ± 0.07	5.53 ± 0.04	3.12 ± 0.03	1.82 ± 0.02

Table 3. *The total electron-loss-weighted cross sections per atom compared with the calculated cross sections in units of 10^{-18} cm^2*

Target gas	Experiment	Born	Classical	Experiment	Born	Classical
	10.2 MeV/amu Ar^{+6}			19 MeV/amu Ar^{+8}		
He	5.61 ± 0.23	3.13	4.23	1.59 ± 0.14	1.00	1.13
N_2	33.4 ± 0.2	23.8	30.7	8.04 ± 0.09	7.73	9.55
Ar	100.5 ± 0.4	104	106	34.4 ± 0.4	36.4	40.3
Xe	215 ± 3	633	358	89.4 ± 0.8	234	157
	30 MeV/amu He^{+1}			38 MeV/amu N^{+6}		
He	0.49 ± 0.07	0.30	0.69	0.06 ± 0.01	0.044	0.046
N_2	1.92 ± 0.10	2.4	4.1	0.34 ± 0.04	0.34	0.36
Ar	7.3 ± 0.4	9.0	11.5	1.64 ± 0.03	1.58	1.58
Xe	23 ± 1	47	36	6.29 ± 0.04	10.30	6.50

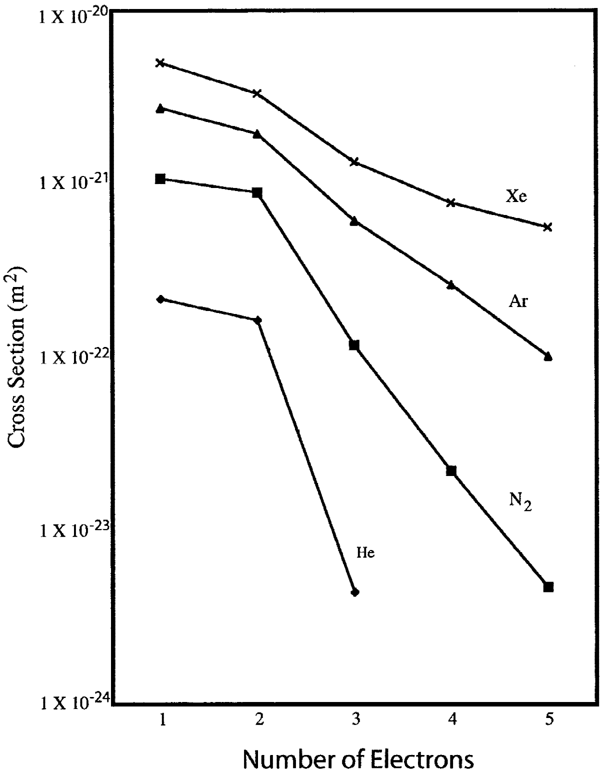

Fig. 1. Cross section per atom versus number of electrons lost in He, N_2, Ar, and Xe by a 10.2 MeV/amu Ar^{+6} beam.

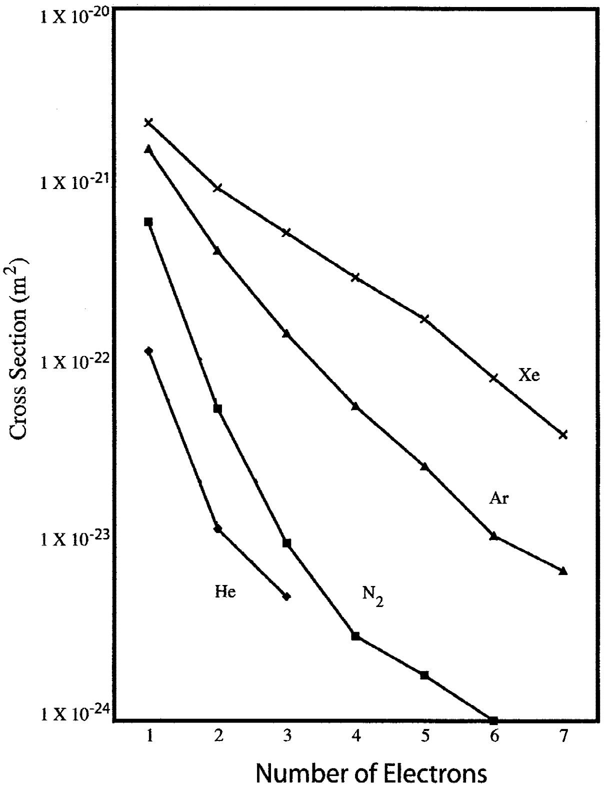

Fig. 2. Cross section per atom versus number of electrons lost in He, N_2, Ar, and Xe by a 19 MeV/amu Ar^{+8} beam.

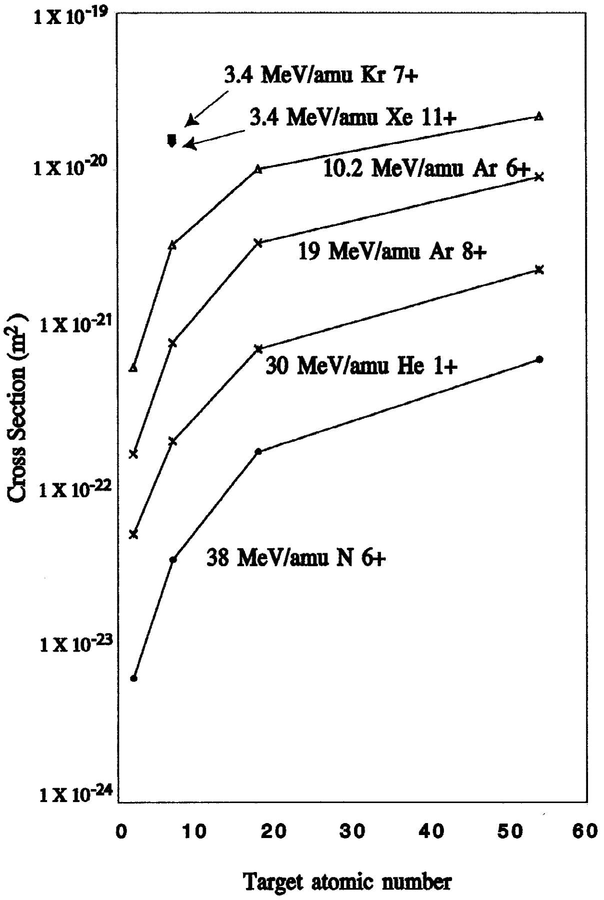

Fig. 3. Weighted cross section per atom versus atomic number of the target gas for the various beams used.

potential for the electron distribution function. Therefore, as expected, agreement with experiment is not as good for Ar as it is for N^{+6}, where these functions are exact. More accurate calculations that account for the exact orbital electron distribution functions and ionization probabilities will be performed in the near future.

The approximation used neglects the larger ionization potential for removal of multiple electrons. This leads to an overestimate in the calculation, especially for the case of Xe, where multiple electron events are more important. Table 3, which includes the total weighted cross sections for each gas and the three beam ion species used in this experiment, shows that both approximations give good estimates, except for the Xe case. The good agreement with experiment for the classical calculation suggests that tunneling transitions do not provide a major contribution to the cross section. This is not expected to be the case for ionized targets and/or low ionization potentials of the projectile (see, e.g., He data in Table 3), where classical calculations would strongly underestimate the cross section (Kaganovich *et al.*, 2002). New experiments are needed to further check these theoretical predictions.

4. CONCLUSIONS

We have measured the electron stripping cross sections for a variety of ion beam energies and species using different target gases. Together with the Xe data of Olson *et al.* (2002), this provides a broad range over which to test the theoretical calculations of the electron stripping of proposed heavy ion drivers for inertial confinement fusion by background gas in the target chamber.

ACKNOWLEDGMENTS

We gratefully acknowledge the staff at the Texas A&M Cyclotron Institute, especially Don May and George Kim, who proved invaluable in providing the desired ion beam species. This research was supported by U.S. DOE Contract No. DE-AC0276CH03073 and the Robert A. Welch Foundation.

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