FINAL TECHNICAL REPORT

ABSOLUTE EXPERIMENTAL CROSS SECTIONS FOR THE
ELECTRON IMPACT SINGLE, DOUBLE, TRIPLE, AND
QUADRUPLE IONIZATION OF Cs^+ IONS

MASTER

prepared by

R. K. Feeney

D. R. Hertling

for the

OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee 37830

operated by

UNION CARBIDE CORPORATION

for the

DEPARTMENT OF ENERGY

Contract No. W-7405-eng-26

February 28, 1981

GEORGIA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL ENGINEERING

ATLANTA, GEORGIA 30332

1981

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ABSOLUTE EXPERIMENTAL CROSS SECTIONS
for the
ELECTRON IMPACT SINGLE, DOUBLE, TRIPLE, AND QUADRUPLE
IONIZATION OF Cs^+ IONS

prepared by

R. K. Feeney
and
D. R. Hertling

of the

SCHOOL OF ELECTRICAL ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia 30332

for the

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830

operated by

UNION CARBIDE CORPORATION

for the

DEPARTMENT OF ENERGY
Contract No. W-7405-eng-26

February 28, 1981

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MGW

TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	iii
LIST OF ILLUSTRATIONS.	iv
ABSTRACT	1
SECTION	
I. INTRODUCTION.	2
II. EXPERIMENTAL APPARATUS AND TECHNIQUE.	5
III. CONSISTENCY CHECKS AND EXPERIMENTAL RESULTS	10
Consistency Checks	
Experimental Results and Discussion of Errors	
IV. COMPARISON WITH AVAILABLE RESULTS	26
V. EXTRAPOLATION TO HIGHER ELECTRON ENERGIES	31

LIST OF TABLES

	<u>Page</u>
Table 1. Absolute Experimental Cross Sections for the Electron Impact Single Ionization of Cs^+ Ions.	12
Table 2. Absolute Experimental Cross Sections for the Electron Impact Double Ionization of Cs^+ Ions.	15
Table 3. Absolute Experimental Cross Sections for the Electron Impact Triple Ionization of Cs^+ Ions.	18
Table 4. Absolute Experimental Cross Sections for the Electron Impact Quadruple Ionization of Cs^+ Ions . . .	21
Table 5. Extrapolated Cross Sections.	34

LIST OF ILLUSTRATIONS

	<u>Page</u>
Figure 1. Schematic Diagram of the Crossed Beam Experiment . . .	6
Figure 2. Absolute Experimental Cross Sections for the Electron Impact Single Ionization of Cs^+ Ions.	14
Figure 3. Absolute Experimental Cross Sections for the Electron Impact Double Ionization of Cs^+ Ions.	17
Figure 4. Absolute Experimental Cross Sections for the Electron Impact Triple Ionization of Cs^+ Ions.	20
Figure 5. Absolute Experimental Cross Sections for the Electron Impact Quadruple Ionization of Cs^+ Ions . . .	22
Figure 6. Absolute Experimental Cross Sections for the Single, Double, Triple, and Quadruple Ionization of Cs^+ Ions.	23
Figure 7. Comparison of the Present Experimental Results with the Experimental Data of Peart and Dolder	27
Figure 8. Comparison of the Present Experimental Results for Single Ionization with Calculations by the Method of Gryzinski.	29
Figure 9. Comparison of the Present Results for Double Ionization with Calculations by the Method of Gryzinski.	30
Figure 10. Bethe-Born Plot for the Single and Double Ioniza- tion of Cs^+ Ions	32
Figure 11. Bethe-Born Plot for the Triple and Quadruple Ionization of Cs^+ Ions	33

ABSTRACT

The absolute cross sections for the single, double, triple and quadruple ionization of Cs^+ ions by electron impact have been measured from below their respective thresholds to approximately 5000 eV. This determination has been accomplished using a crossed beam facility in which monoenergetic beams of ions and electrons are caused to intersect at right angles in a well-defined collision volume. Multiply charged, product ions born as a result of the electron impact are deflected into their respective detectors by cascaded electrostatic analyzers. The multiply charged beam current component is measured by means of a vibrating reed electrometer operating in the rate-of-charge mode.

The required singly charged cesium ions are produced in a thermionic ion source and pass through a series of focusing, collimating and deflecting structures before entering the interaction region. A thermionically generated, rectangular electron beam intercepts the target ions in a spatially designated collision volume. Just prior to entering this interaction region the two beams can be made to pass through a movable slit scanner which determines their spatial profiles. The various charged particle currents, energies and beam current density distributions represent the experimental data from which the desired absolute cross sections have been determined. The results obtained with this technique are compared with available experiment and theoretical results.

SECTION I

INTRODUCTION

Absolute cross sections for the electron impact of single, double, tripple, and quadruple ionization of Cs^+ ions have been measured from below their respective thresholds to approximately 5000 eV. The measurements were made using a crossed beam facility in which monoenergetic beams of ions and electrons were caused to intersect in a well-defined collision volume. The various currents, energies, and beam current density distributions constituted the experimental data from which the desired cross sections were determined.

This work was undertaken to provide calibration data for the ion beam probe currently being utilized on the ELMO Bumpy Torus Scale (EBT-S). Such ion beam probes are proving to be extremely versatile and valuable plasma diagnostic tools. Probes can measure plasma density, space potential, charge and current density, electric and magnetic fields, and electron temperature.¹⁻⁶ The technique permits plasma parameters to be resolved both in space and time.

Most of the ion beam probes have relied upon the use of singly-charged probe-ions and doubly-charged product-ions, i.e., a single ionization event. Electron temperature measurements are usually made by simultaneously injecting two species of ions into the plasma. If the cross section of each ion has a different variation with electron energy, the ratio of the two is independent of the electron density, and is a unique function of electron temperature. In certain situations it is advan-

tageous to use the simultaneous ionization of a single probe species to different charge states. The advantage of this technique is the higher electron temperature that can be measured because of the greater threshold energy for multiple ionization.

The validity of a probe utilizing simultaneous ionization of the single species was demonstrated with a Rb^+ ion beam probe applied to an earlier configuration of the EBT machine. In that experiment, Rb^{2+} , Rb^{3+} , Rb^{4+} , and possibly Rb^{5+} product ions were observed.^{7,8} The larger magnetic field of the EBT-S experiment requires a heavier ion to assure penetration of the plasma with the available ion beam acceleration energy. Hence, singly-charged Cs ions were selected as probe-ions for the EBT-S machine.

The quantitative results obtained from ion beam probes are critically dependent upon the accuracy with which the required cross sections are known. Measured electron impact single ionization cross sections are available for all of the alkali ions and for thallium.⁹⁻¹⁸ However, Li^+ double ionization data, and recently, Rb^+ double, triple, and quadruple ionization cross sections are the only electron impact multiple ionization results that are known.^{19,20} In addition, there is a disagreement between the previously determined cross section data for the single ionization of Cs^+ ions.^{15,16}

No calculated cross sections are known for the single and multiple ionization of Cs^+ ions. The semiclassical theory of Gryzinski and the empirical method of Lotz have been used by plasma workers to obtain estimates of ionization cross sections.²¹⁻²³ These techniques are typically within a factor of two of the experimental results for single and double

ionization. Unfortunately, there are no estimates of any type for triple and higher order ionization processes.

Because of the lack of reliable theoretical values, measured cross sections are essential for valid beam probe diagnostics. Accordingly, the present measurements of the electron impact single, double, and triple ionization cross sections of Cs^+ ions were undertaken. This report presents a discussion of the experimental apparatus and method, a discussion of the consistency checks and experimental results, and a comparison of the present results with available approximate theoretical predictions. An extrapolation of the measured results to higher electron energies is also included.

SECTION II

EXPERIMENTAL APPARATUS AND TECHNIQUE

The electron impact single, double, triple, and quadruple ionization cross sections of Cs^+ have been measured as a function of incident electron energy from below threshold to approximately 5000 eV.

The experimental method involves the use of a crossed beam apparatus in which approximately monoenergetic beams of ions and electrons are caused to intersect at right angles in a well-defined collision region. The crossed beam technique has now become a well-established tool for the study of charged-particle--charged-particle collision processes. Several reviews that discuss the advantages and difficulties inherent in crossed beam experiments have been written and most of the early work utilizing this method has been critically evaluated.^{9,10,24-26} Accordingly, with the availability of such a complete body of reference material, a general discussion of the experimental technique will not be given here; however, those unique problems associated with the proposed experiment are discussed in appropriate sections.

A schematic diagram of the experimental apparatus is given in Figure 1. Singly charged cesium ions are thermionically generated in an alumniosilicate-molybdenum plug rigidly mounted behind a Pierce-type electrostatic gun. This combination produces an intense, highly collimated beam of Cs^+ ions in the ionic ground state which subsequently receive additional collimation and focusing in the F_1 and F_2 structures. Just before entering the collision volume C, this primary beam is deflected

Figure 1. Schematic Diagram of the Crossed Beam Experiment.

through a slight angle by the F_3 stage in order to remove any neutral atoms or ions which have become multiply charged as a result of stripping on slit edges or residual gas molecules. A rectangular electron beam is produced by a 6L6GC beam power tube and intersects the Cs^+ beam in the spatially designated collision volume, C. Prior to entering this interaction region the two beams can be made to pass through a movable slit scanner, S, which determines their respective current density profiles.

After undergoing collision, the ion beam, which might now contain a number of charge state components, passes through the entrance aperture of the primary electrostatic analyzer. Note that the much greater mass of the Cs^+ ions makes it possible to ensure that any interaction with the electron beam results in small-angle scattering of the ions. Hence, those ions which have undergone interaction with the electrons emerge from the collision volume with essentially the same velocity as that of the unreacted ions making the resulting beam amenable to electrostatic analysis. The multiply charged ions are subsequently deflected through the secondary electrostatic analyzer and thence into the N^+ Faraday cup. By simply scaling the analyzer potentials, it is possible to monitor any multiply-charged signal current in the N^+ cup while the singly-charged beam is simultaneously deflected into the auxiliary cup. This capability enables the cross sections for various electron impact ionization processes of interest to be determined without mechanically altering the experimental apparatus. The creation of such a "universal" experiment has considerably reduced the amount of time required to measure the various ionization cross sections for a particular ionic species.

In this experiment, as in certain of our previous work,^{9,20} a 6L6GC beam tetrode is used as an electron source. The tube envelope is first removed except for the base portion which supports the tube structure. One side of the plate is then opened to expose the grids and beam forming structure. A clamping fixture holds the tube in position while allowing the electron beam to exit from the beam forming structure, through several apertures, and into the interaction region. The source is capable of providing a 2.5 mm thick electron beam of 1 mA at 150 eV and more than 10 mA at 1000 eV. The mean energy of the electron beam is about 2 eV below that set by the acceleration voltage while the energy spread is about 1 eV at half-maximum.

The required quantity of singly charged Cs^+ ions is produced thermionically in an aluminosilicate-molybdenum pellet.²⁷ Metallurgically similar sources have also been developed for all the remaining alkali ions and for thallium. The complete emitter assembly is mounted behind a specially designed, five-element, Pierce-type focusing structure. This thermionic ion source produces a chemically pure beam of ground state alkali ions. No differential pumping or water cooling is required with this type of source. The ion source has been found to produce a uniform beam of $2-5 \times 10^{-7}$ A for an operating period of several weeks. Impurity levels are always less than 0.5% of the desired ion emission current.

The electron current is determined from the voltage drop across a precision resistance as monitored with a digital voltmeter. The error in the electron current determination is less than $\pm 1\%$. The singly charged ion beam current is measured with a conventional electrometer while the multiply charged ion beam current is measured with a vibrating reed elec-

trometer operating in the rate-of-charge mode. The estimated error in the singly and multiply charged ion beam currents is less than $\pm 2\%$ and $\pm 3\%$, respectively.

The experiment was operated in the pulsed-beam mode.¹⁰ This technique eliminated background gas-density modulation effects which otherwise might occur when the vacuum system pressure were greater than about 10^{-8} Torr. Both the ion beam and the electron beam were pulsed, the ion beam with a 40% duty factor and the electron beam with a 50% duty factor. By a simple change of the relative phases of the two beams, the ions and electrons could be made to cross the interaction region either in time coincidence or in time anticoincidence. The difference between the coincidence and anticoincidence signals gave the electron impact ionization current.

SECTION III

CONSISTENCY CHECKS AND EXPERIMENTAL RESULTS

The cross section for ionization of singly charged ions by electron impact is obtained from the observed experimental quantities by the relationship,

$$\sigma_{1N} = \frac{I_{SIG}^{N+}}{JI^+} \frac{e V_i V_e F}{N(V_i^2 + V_e^2)^{1/2}} \quad (1)$$

where

$$F = \frac{\int_{-\infty}^{\infty} i(z) dz \int_{-\infty}^{\infty} j(z) dz}{\int_{-\infty}^{\infty} i(z) j(z) dz} \quad (2)$$

In this equation V_i and V_e are the ion and electron velocities; I^+ and J are the total ion and electron electric currents; $i(z)dz$ and $j(z)dz$ are the ion and electron currents passing through the region z to $z + dz$; I_{SIG}^{N+} is the total electric current of multiply charged ions produced by electron impact; and e is the magnitude of the electron charge. The factor, F , known as the form factor, is usually approximated by simultaneously scanning both beams with an L-shaped probe having coplanar slits.

Most of the parameters in Eq. (1) can be routinely evaluated; however, serious difficulties may be encountered in the measurements of I_{SIG}^{N+} and F . In order to assure that the electron impact ionization signal and the form factor are being measured correctly, it is necessary to apply a series of consistency checks. Details of those checks applicable to charg-

ed-particle--charged-particle crossed beam experiments are discussed elsewhere.^{9,10,24-26}

Consistency Checks

It is important that the measured cross sections be independent of the particular values of the quantities in Eq. (1). In addition, the measured cross section should be zero below threshold. During the operation of the experiment, the ion and electron currents were randomly varied over a 10-1 range with no systematic effect on the measured cross sections. The ion beam energy was also switched between 1.0 and 1.5 keV with no effect on the experimental results. There was likewise no systematic variation of the measured cross sections for changes in the form factor. Periodic measurements of the cross section below threshold established a zero value within the allowable experimental error.

The lack of systematic variation of the cross section with changes in the particle currents and ion beam energy showed that adverse focusing effects were not present.^{9,10,24-26} The zero cross section below threshold further established the absence of focusing and also excluded the presence of background pressure modulation.^{9,10,24-26}

Experimental Results and Discussion of Errors

Absolute cross sections for the double, triple and quadruple ionization of Cs^+ ions by electron impact have been measured for electron energies from below their respective thresholds to approximately 5000 eV. The results of these measurements are summarized in Tables 1-4 and presented graphically in Figures 2-5, respectively. Figure 6 reproduces all three of the cross sections on a single plot in order to facilitate comparison of

TABLE 1. Absolute Experimental Cross Sections for the
Electron Impact Single Ionization of Cs⁺ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10^{-16} cm^2	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
25	23 $\pm$ 1	0.0	-	-	-
30	28 $\pm$ 1	1.21	$\pm$ 11	$\pm$ 8	$\pm$ 19
35	33 $\pm$ 1	1.67	$\pm$ 12	$\pm$ 8	$\pm$ 20
40	38 $\pm$ 1	1.97	$\pm$ 7	$\pm$ 8	$\pm$ 15
50	48 $\pm$ 1	2.09	$\pm$ 5	$\pm$ 8	$\pm$ 13
60	58 $\pm$ 1	2.05	$\pm$ 7	$\pm$ 8	$\pm$ 15
70	68 $\pm$ 1	2.09	$\pm$ 6	$\pm$ 8	$\pm$ 14
80	78 $\pm$ 1	2.11	$\pm$ 5	$\pm$ 8	$\pm$ 13
90	88 $\pm$ 1	2.11	$\pm$ 5	$\pm$ 8	$\pm$ 13
100	98 $\pm$ 1	2.09	$\pm$ 5	$\pm$ 8	$\pm$ 13
120	118 $\pm$ 1	1.91	$\pm$ 5	$\pm$ 8	$\pm$ 13
140	138 $\pm$ 1	1.72	$\pm$ 6	$\pm$ 8	$\pm$ 14
170	168 $\pm$ 1	1.61	$\pm$ 5	$\pm$ 8	$\pm$ 13
200	198 $\pm$ 2	1.53	$\pm$ 5	$\pm$ 8	$\pm$ 13
220	218 $\pm$ 2	1.37	$\pm$ 5	$\pm$ 8	$\pm$ 13
250	248 $\pm$ 2	1.27	$\pm$ 7	$\pm$ 8	$\pm$ 15
300	298 $\pm$ 2	1.19	$\pm$ 5	$\pm$ 8	$\pm$ 13

TABLE 1. Absolute Experimental Cross Sections for the
Electron Impact Single Ionization of Cs⁺ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10 ⁻¹⁶ cm ²	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
400	398 ± 2	0.939	± 6	± 8	± 14
500	498 ± 2	0.820	± 6	± 8	± 14
600	598 ± 3	0.716	± 6	± 8	± 14
750	748 ± 3	0.632	± 7	± 8	± 15
1000	998 ± 4	0.515	± 6	± 8	± 14
1500	1498 ± 5	0.364	± 5	± 8	± 13
2000	1998 ± 6	0.290	± 5	± 8	± 13
3000	2998 ± 9	0.200	± 5	± 8	± 13
4000	3998 ± 11	0.154	± 5	± 8	± 13
5000	4998 ± 14	0.131	± 5	± 8	± 13

Figure 2. Absolute Experimental Cross Sections for the Electron Impact Single Ionization of Cs^+ Ions.

TABLE 2. Absolute Experimental Cross Sections for the
Electron Impact Double Ionization of Cs⁺ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10 ⁻¹⁷ cm ²	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
50	48 ± 1	0.0	-	-	-
60	58 ± 1	0.0	-	-	-
70	68 ± 1	0.398	± 12	± 8	± 20
80	78 ± 1	0.717	± 7	± 8	± 15
90	88 ± 1	1.32	± 8	± 8	± 16
100	98 ± 1	2.46	± 7	± 8	± 15
120	118 ± 1	3.74	± 5	± 8	± 13
140	138 ± 1	3.57	± 6	± 8	± 14
170	168 ± 1	3.03	± 5	± 8	± 13
200	198 ± 2	2.76	± 5	± 8	± 13
220	218 ± 2	2.56	± 5	± 8	± 13
250	248 ± 2	2.44	± 7	± 8	± 15
300	298 ± 2	2.50	± 5	± 8	± 13
400	398 ± 2	2.36	± 5	± 8	± 13
500	498 ± 2	2.25	± 5	± 8	± 13
600	598 ± 3	2.07	± 6	± 8	± 14
750	748 ± 3	1.93	± 5	± 8	± 13

TABLE 2. Absolute Experimental Cross Sections for the
Electron Impact Double Ionization of Cs^+ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10^{-17} cm^2	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
1000	998 ± 4	1.72	± 5	± 8	± 13
1500	1498 ± 5	1.40	± 5	± 8	± 13
2000	1998 ± 6	1.19	± 5	± 8	± 13
3000	2998 ± 9	0.891	± 5	± 8	± 13
4000	3998 ± 11	0.719	± 5	± 8	± 13
5000	4998 ± 14	0.613	± 5	± 8	± 13

Figure 3. Absolute Experimental Cross Sections for the Electron Impact Double Ionization of Cs^+ Ions.

TABLE 3. Absolute Experimental Cross Sections for the
Electron Impact Triple Ionization of Cs⁺ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10^{-18} cm^2	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
100	98 ± 1	0.0	-	-	-
120	118 ± 1	1.06	± 5	± 8	± 13
140	138 ± 1	3.85	± 5	± 8	± 13
170	168 ± 1	5.70	± 5	± 8	± 13
200	198 ± 2	7.56	± 5	± 8	± 13
220	218 ± 2	8.26	± 5	± 8	± 13
250	248 ± 2	7.57	± 6	± 8	± 14
300	298 ± 2	7.21	± 5	± 8	± 13
400	398 ± 2	6.53	± 5	± 8	± 13
500	498 ± 2	5.93	± 7	± 8	± 15
600	598 ± 3	5.31	± 6	± 8	± 14
750	748 ± 3	4.46	± 5	± 8	± 13
1000	998 ± 4	3.62	± 5	± 8	± 13
1500	1498 ± 5	2.70	± 5	± 8	± 13
2000	1998 ± 6	2.21	± 5	± 8	± 13
3000	2998 ± 9	1.53	± 5	± 8	± 13

TABLE 3. Absolute Experimental Cross Sections for the
Electron Impact Triple Ionization of Cs⁺ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10^{-18} cm^2	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
4000	3998 ± 11	1.17	± 5	± 8	± 13
5000	4998 ± 14	0.926	± 6	± 8	± 14

Figure 4. Absolute Experimental Cross Sections for the Electron Impact Triple Ionization of Cs^+ Ions.

TABLE 4. Absolute Experimental Cross Sections for the
Electron Impact Quadruple Ionization of Cs⁺ Ions

Indicated Electron Energy, eV	Actual Electron Energy, eV	Cross Section Units of 10^{-18} cm^2	90 Per Cent Confidence Limits, Per Cent	Total Systematic Error, Per Cent	Total Worst-Case Error, Per Cent
170	168 ± 1	0.0	-	-	-
200	198 ± 2	0.348	± 13	± 8	± 21
220	218 ± 2	0.923	± 5	± 8	± 13
250	248 ± 2	1.52	± 5	± 8	± 13
300	298 ± 2	2.10	± 5	± 8	± 13
400	398 ± 2	2.06	± 6	± 8	± 14
500	498 ± 2	2.03	± 8	± 8	± 16
600	598 ± 3	1.94	± 6	± 8	± 14
750	748 ± 3	1.77	± 5	± 8	± 13
1000	998 ± 4	1.50	± 7	± 8	± 15
1500	1498 ± 5	1.25	± 5	± 8	± 13
2000	1998 ± 6	1.05	± 5	± 8	± 13
3000	2998 ± 9	0.783	± 5	± 8	± 13
4000	3998 ± 11	0.592	± 6	± 8	± 14
5000	4998 ± 14	0.499	± 7	± 8	± 15

Figure 5. Absolute Experimental Cross Sections for the Electron Impact Quadruple Ionization of Cs^+ Ions.

Figure 6. Absolute Experimental Cross Sections for the Electron Impact Single, Double, Triple, and Quadruple Ionization of Cs^+ Ions.

the characteristic structure peculiar to each ionization process. In all cases, only the actual measured values are presented and no assumptions have been made about the magnitudes of the cross sections intermediate to the sampled electron energies. The worst-case uncertainties in the resulting cross sections are indicated in both the tables and the figures and the error analysis employed to evaluate their extent is discussed below.

Systematic errors arise from the uncertainty in the electron beam energy, the uncertainty in the ion beam energy, and from the calibration of the measurement instruments.

As mentioned previously, the energy of the emitted electrons is estimated to be 2 ± 1 eV below the indicated electron acceleration energy with a FWHM of about 1 eV. The uncertainty in the electron energy resulting from the internal oxide cathode potential drop and the electron acceleration energy power supply calibration are accounted for in the tabular data. The 2 volt energy degradation is reflected in the graphical data but the uncertainty in the electron energy is not indicated.

The estimated systematic error in the ion beam energy is the sum of the error in the ion beam acceleration potential and the voltage drop across the ion emitter pellet. This results in an ion beam energy error of less than 1%. Since the measured cross section varies with the ion velocity and hence as the square root of the ion energy, the systematic error in the cross section measurement from this cause is less than 0.5%. The calibration errors characteristic of the instruments used in the present experiment are added to yield and estimate of the overall instrumentation accuracy. The resulting systematic uncertainty arising from instrumentation errors is taken to be $\pm 7\%$. Finally, the overall systematic error is

taken to be the sum of the beam energy errors and the calibration errors. These have been combined to yield a worst-case systematic error in the measured cross sections $\pm 8\%$.

The magnitudes of the random errors inherent in the present experimental results have been estimated from the 90% confidence limits of the mean.²⁸ This component of the overall experimental uncertainty arises because seemingly equivalent measurements generally yield slightly different cross sections. For instance, similar data runs made over a short period of time typically display a random variation of perhaps $\pm 3\%$. Cross sections resulting from measurements performed over longer periods, however, tend to fluctuate on the order of $\pm 5-7\%$ about the eventual sample mean. These larger variations are presumed to arise from the electron source peculiarities characteristic of the cathode used during that particular pumpdown of the apparatus. Since every energy was not sampled uniformly on every pumpdown the above variations sometimes caused adjacent data points to exhibit significantly different confidence limits. This difference was accounted for by arbitrarily setting the minimum confidence limit to $\pm 5\%$.

The resulting estimate of the random error has been added to the previously discussed systematic error in order to obtain the corresponding worst case error. These total errors are then appended to the final experimental results and appear in both the tabular and graphical presentations of the measured cross sections.

SECTION IV

COMPARISON WITH AVAILABLE RESULTS

No quantum mechanical calculations exist for any of the processes considered in this work, but the semiclassical Gryzinski method can be used to obtain approximate results for the single and double ionization cross sections.²¹ The only experimental results are those by Peart and Dolder for single ionization.¹⁶ This section compares the present data with these measured and calculated cross sections.

The present results for single ionization of Cs^+ ions are compared with the experimental results of Peart and Dolder in Figure 8. It is seen that the present work agrees well with the experimental data of Peart and Dolder near the peak of the cross section, but the two results diverge at higher and lower energies. There is no obvious explanation for this behavior, but a discussion of relevant factors is presented below.

During the course of the present work all consistency checks required by the experimental technique were always satisfied. Particularly, the cross section below threshold was measured frequently and always found to have an absolute value of less than 1% of the peak cross section. Positive and negative values occurred with approximately equal frequency giving a very small average cross section. Cross sections measured above threshold, using electron and ion beam currents comparable to those used below threshold, gave consistently positive and reproducible results. Since ionic impurities that would cause an inflated cross section would have a lower threshold energy, it must be concluded that such impurities

Figure 7. Comparison of the Present Experimental Results with the Experimental Data of Peart and Dolder.

were not present in significant quantities. This conclusion was reinforced by mass spectrometric analysis of the ion emitter. Initial fluxes of K^+ and Na^+ ions were observed, but these rapidly decayed with time. Another sensitive check, x-ray fluorescence analysis, was performed on the emitter material. No low ionization potential impurities such as Tl were observed. Since the presence of K^+ and Na^+ ions would cause the apparent cross section to be too small, it is impossible that their presence could lead to the disagreement with the results of Peart and Dolder.

As a final observation, it is noted that preliminary measurements of the single ionization of Cs^+ ions were obtained as part of a previous program.¹⁵ Another apparatus, having different ion and electron sources, was used in that work. The previous results agree very well with the present data and exhibit the same disagreement with the results of Peart and Dolder. It is also interesting that results for the single ionization of Rb^+ ions, obtained with the earlier apparatus, agreed very well with the similar results of Peart and Dolder.¹⁸

Calculations made using the semiclassical method of Gryzinski are shown in Figure 9. Contributions to the cross sections from the 5p, 5s, 4d, and 4p subshells are included. The agreement is seen to be poor at low energies and near the peak, but good at the higher energies.

Gryzinski-method calculations are shown in Figure 10. for the double ionization of Cs ions. These Gryzinski data are always significantly below the measured values, which may be because the simple Gryzinski theory does not consider all possible ionization processes.

No calculations or experimental data are available for the higher order ionization processes.

Figure 8. Comparison of the Present Experimental Results for Single Ionization with Calculations by the Method of Gryzinski.

Figure 9. Comparison of the Present Experimental Results for Double Ionization with Calculations by the Method of Gryzinski.

SECTION V

EXTRAPOLATION TO HIGHER ENERGIES

Many plasma applications of cross sections require that the cross sections be convolved with an electron velocity distribution to produce rate coefficients. In some cases the high energy "tail" of the velocity distribution may be sufficiently large that cross section values for electron energies greater than the measured values are required. An estimate of these needed high energy cross sections may be obtained by extrapolating the measured data by use of the Bethe-Born approximation.²⁹

The Bethe-Born approximation for direct ionization by fast electrons gives for the cross section,

$$\sigma = \frac{A}{E} \log(BE)$$

where E is the electron energy, and A and B are constants for a particular atomic system and ionization process. The equation can be rewritten as

$$\sigma AE = \log(BE)$$

This latter equation is a straight line when σE is plotted as a function of $\log(E)$. Figures 10 and 11 give such a Bethe-Born plot for the measured cross sections. The curves are seen to nearly approach a straight line for electron energies greater than about 1500 eV. Also shown on the graphs are

Figure 10. Bethe-Born Plot for the Single and Double Ionization of Cs⁺ Ions.

Figure 11. Bethe-Born Plot for the Triple and Quadruple Ionization of Cs^+ Ions.

straight lines fitted to the higher five (six for σ_{12}) data points. These lines were used to obtain the extrapolated cross sections given in Table 5.

Table 5. Extrapolated Cross Sections

Energy (keV)	Cross Section			
	σ_{12} (10^{-18} cm^2)	σ_{13} (10^{-18} cm^2)	σ_{14} (10^{-19} cm^2)	σ_{15} (10^{-19} cm^2)
10	7.02	3.62	5.07	2.86
15	4.90	2.62	3.50	2.04
20	3.97	2.08	2.70	1.60
50	1.66	0.977	1.16	0.730
100	0.885	0.543	0.615	0.399

In the absence of measured data, these extrapolated cross sections may be used for rate coefficient calculations at higher electron energies. However, it should be remembered that these values are only estimates and should be treated accordingly.

REFERENCES

1. F. C. Jobs and R. L. Hickok, Nucl. Fusion, 10, 195 (1970).
2. F. C. Jobs, J. F. Marshall, and R. L. Hickok, Phys. Rev. Letters 22, 1042 (1969).
3. R. E. Reinovsky, W. C. Jennings, and R. L. Hickok, Phys. Fluids 16, 1772 (1973).
4. R. E. Reinovsky, J. C. Glowienka, A. E. Seaver, W. C. Jennings, and R. L. Hickok, IEEE Trans. Plasma Sci. PS-2, 250 (1974).
5. J. H. Stufflebeam, W. C. Jennings, K. A. Connor, and R. L. Hickok, Development of a Beam Probe Diagnostic System for the United Aircraft "LITE" Program, RPD L Report No. 85-12a, RPI (1975).
6. G. X. Kambic, IEEE Trans. Plasma Sci. PS-4, 1, (1976).
7. P. L. Colestock, K. A. Connor, and R. L. Hickok, Phys. Rev. Letters 40, 1717 (1978).
8. K. A. Connor, Private Communication.
9. W. C. Lineberger, J. W. Hooper, and E. W. McDaniel, Phys. Rev. 141, 151 (1966).
10. J. W. Hooper, W. C. Lineberger, and F. M. Bacon, Phys. Rev. 141, 165 (1966).
11. J. B. Wareing and K. T. Dolder, Proc. Phys. Soc., London 91, 887 (1967).
12. B. Peart and K. T. Dolder, J. Phys. B 1, 240 (1968).
13. B. Peart and K. T. Dolder, J. Phys. B 1, 872 (1968).
14. R. K. Feeney, J. W. Hooper, and M. T. Elford, Phys. Rev. A 6, 1469 (1972).
15. W. E. Sayle, II, R. K. Feeney, and T. F. Divine, Abstracts of Papers of the IXth International Conference on the Physics of Electronic and Atomic Collisions, edited by J. S. Risley and R. Geballe, (University of Washington Press, Seattle. 1975), p. 895.
16. B. Peart and K. Dolder, J. Phys. B 8, 56 (1975).

17. T. F. Divine, R. K. Feeney, W. E. Sayle, II, and J. W. Hooper, Phys. Rev. A 13, 54 (1976).
18. R. K. Feeney, W. E. Sayle, II, and T. F. Divine, Phys. Rev. A 18, 82 (1978).
19. B. Peart and K. T. Dolder, J. Phys. B 2, 1169 (1969).
20. D. W. Hughes and R. K. Feeney, Absolute Experimental Cross Sections for the Electron Impact Ionization of Rubidium, Report No. ORO-3027-52, USDOE, Georgia Institute of Technology, March 1980.
21. M. Gryzinski, Phys. Rev. 138, A336 (1965).
22. W. Lotz, Z. Physik 206, (1967).
23. W. Lotz, Z. Physik 216, 241 (1968).
24. G. H. Dunn, Atomic Physics, edited by B. Bederson, V. W. Cohen, and F. M. J. Pichanick (Plenum Press, New York, 1969), pp. 417-433.
25. M. F. A. Harrison, Brit. J. Appl. Phys. 17, 371 (1966).
26. K. T. Dolder, Case Studies in Atomic Collision Physics, Volume 1, edited by E. W. McDaniel and M. R. C. McDowell (North Holland Pub. Co., Amsterdam, 1969), pp. 251-330.
27. D. W. Hughes, R. K. Feeney and D. N. Hill, Rev. Sci. Instrum. 51, 1471 (1980).
28. R. S. Burington and D. C. May, Handbook of Probability and Statistics with Table, 2nd ed. (McGraw-Hill, New York, 1970).
29. E. W. McDaniel, Collision Phenomena in Ionized Gases. (John Wiley, New York, 1964), pp. 322-328.