1972

Ionization mechanisms in cesium

Yu Bong Hahn

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IONIZATION MECHANISMS IN CESIUM

by

YU BONG HAHN, 1942-

A DISSERTATION

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

in

PHYSICS

1972
PREFACE

Because of the rather independent features of the contents in this dissertation, it is divided into three separate parts. The first part, discussing the electron impact excitation of autoionizing levels in cesium, has been published in the Physical Review A 4, 125 (1971). The second part discusses the excitation of 5p-electrons in cesium by electron impact, including direct excitation-ionization mechanism by energetic electrons on neutral cesium resulting in a vuv photon emission or a metastable ion. Parts of the material in this section have been presented at the VII International Conference of Physics of Electronic and Atomic Collisions, Amsterdam, 1971, the 24th Annual Gaseous Electronics Conference, Gainsville, Florida, 1971, and the DEAP Meeting, Atlanta, Georgia, 1971. It will be submitted for publication in the Physical Review. The last section of the dissertation, the appendix, contains a study of the Channeltron gain in magnetic fields, which was rather critical in the investigations in the section two. This study was carried out independently, and part of the material has been accepted for publication in the Review of Scientific Instruments and is presently in press.

I would like to acknowledge indebtedness to thesis advisor, Dr. Kaare J. Nygaard, for his suggestions and continuing guidance, without which the completion of this work would not have been possible.

Special thanks are due to Daniel Kastelein for his technical assistance, and to my colleagues Beaufort Lancaster and Robert E. Hebner, Jr. for their day to day assistance. I also would like to thank the Faculty of the physics department for many valuable
contributions which enabled me to complete my course of study in Rolla. I appreciate the financial support received through the department of physics, University of Missouri-Rolla, which made possible the completion of this project.

Lastly, I would like to thank my wife, Myung-Ok, for her patience and encouragement during the many difficult times.
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PART A

ELECTRON IMPACT EXCITATION OF AUTOIONIZING LEVELS IN CESIUM

(Published in the Physical Review A 4, 125, 1971)
ABSTRACT

Electron Impact Excitation of Autoionizing Levels in Cesium

Autoionizing states in Cs between 12 and 20 eV have been studied by electron impact. The retarding-potential-difference (RPD) method was used to obtain an electron beam with energy spread of about 0.1 eV. To determine the threshold energies, inelastically scattered electrons were analyzed by the trapped-electron method. We have been able to identify about 20 levels, and the agreement with spectroscopic data is excellent. A peak appearing at 12.80 eV is probably due to the quartet states observed by Feldman and Novick.
I. INTRODUCTION

The structure that is sometimes seen in electron-impact ionization curves, as well as certain anomalies in vacuum ultraviolet absorption experiments, can in many cases be attributed to the process of auto-ionization. Series of auto-ionizing levels in atoms and molecules result from the excitation of an inner-core electron or from the simultaneous excitation of two electrons. The levels are located above the first ionization potential and can, in principle, decay via one of the following two channels: (i) by a radiative transition to a bound state of the atom below the ionization potential, or (ii) by a non-radiative transition to the ground state or to one of the excited states of the ion. In the nonradiative channel the process leads to the emission of a fast electron whose kinetic energy equals the difference between the energies of the initial and final states. This process is called auto-ionization, and it is the objective of this paper to report on electron-induced auto-ionization in cesium vapor.

In general, auto-ionizing levels\(^1\) can be excited by photons,\(^2\) electrons,\(^5\) ions,\(^9\) and fast atoms,\(^11\) and can also be generated in a hot plasma by dielectronic recombination.\(^12\) For these reasons, auto-ionization plays an important role in the interpretation of far-ultraviolet solar and stellar spectra. One interesting astrophysical aspect of auto-ionization is the extremely short lifetime of some of the levels involved, of the order of $10^{-14}$ sec. This corresponds to a linewidth of about 100 Å, thus making the lines very efficient absorbers. Further details on the astrophysical significance are discussed by Goldberg.\(^13\) The presence of auto-ionizing levels close
FIG. 1. Compilation of cross-section data for production of Cs\(^+\) ions from cesium by electron impact: H + S, Heil and Scott (Ref. 17); K + P, Korchevoi and Przonski (Ref. 18); T + S, relative measurements of Tate and Smith (Ref. 21) normalized to the absolute measurements of Nygaard (Ref. 19); N, Nygaard (Ref. 19); Z + S, Zapesochnyi and Aleksakhin (Ref. 20); ■, Brink (Ref. 16); ●, McFarland and Kinney (Ref. 22); ○, McFarland (Ref. 23).
FIG. 1

Cesium

$\sigma (\text{Å}^2)$ vs Energy (eV)

- K+P
- Z+A
- T+S
- H+S

energies and cross sections for cesium.
to the ionization threshold in a number of metal vapors and gases contributes strongly to the total ionization cross sections both by electron impact\textsuperscript{14} and by photoabsorption\textsuperscript{15}.

In cesium, the lowest auto-ionizing level is located approximately 8 eV above the first ionization potential at 3.89 eV, and this rather isolated level, plus some others, can therefore be studied by electron-energy-loss techniques without too much interference from the ionization of the valence electron. In the literature\textsuperscript{16-23} there are indications that excitation of auto-ionizing levels may partly account for the structure in the cesium ionization cross section, which is shown in Fig. 1. Typical of all results is the pronounced peak around 15 eV. This feature coincides with the existence of a high number of $1^b$ levels\textsuperscript{24} in the energy region between 12 and 19 eV\textsuperscript{2-4}. For completeness, we should add that the broad maximum around 28 eV in Fig. 1 is due to the production of excited ions, whereas the lower maximum observed by Zapesochnyi and Aleksakhin\textsuperscript{20} at 9 eV coincides with the maximum cross section for removal of 6s electrons.

By using the retarding-potential-difference (RPD) gun invented by Fox \textit{et al.}\textsuperscript{25,26} and the trapped-electron method developed by Schulz\textsuperscript{27} we have been able to excite and resolve about 20 of the $1^b$ levels, thereby gaining more knowledge on the ionization mechanisms in cesium.

In Sec. II are described general characteristics of auto-ionization, as well as specific auto-ionizing levels in cesium, the levels being those reported in the pioneering works of Beutler and Guggenheimer\textsuperscript{2} and of Moore\textsuperscript{28}. The apparatus and experimental procedure, the results, data analysis, and discussion are contained in Secs. III and IV.
II. CHARACTERISTICS OF AUTO-IONIZATION

Auto-ionization processes have been observed in simple atomic as well as in complicated molecular systems. When bound electrons gain sufficient energy by some collisional mechanism, the atom may be excited to one of its "discrete" states embedded in the continuum. The decay of these states can be either radiative or nonradiative, the latter process being known as auto-ionization. If the probability of auto-ionization is close to unity, the excited state can no longer be considered discrete because of the strong mixing with the continuum. The line then becomes broadened and the energy indistinct, with corresponding lifetimes of the order of $10^{-13} - 10^{-15}$ sec. On the other hand, long-lived metastable quartet states may exhibit lifetimes of about $10^{-5} - 10^{-6}$ sec, as reported by Feldman and Novick.\(^5\)

In the alkali elements, due to the high binding energy of the inner-core electrons, excitation of any of these may lead to a series of discrete states well beyond the first ionization limit. In cesium, for instance, one of the inner electrons ($5p$) in the $5p^66s$ ground-state configuration becomes excited and results in a bound state with electron configuration $5p^56s6s$. This state ($^2p_{3/2}$) is located 12.3 eV above the ground state of the atom, as illustrated in the simplified-term diagram in Fig. 2, and may decay to the ground state of Cs\(^+\)(\(^1S_0\)) by ejecting a fast electron with a kinetic energy of 8.41 eV. Auto-ionization levels may form Rydberg series, and as an example we show some of the levels with $5p^56s6s$ configuration in Fig. 2. In addition to the $5p6s$ns sequence given as an example here, we have been able to excite and identify several states of other series and discuss these
FIG. 2. Simplified cesium term diagram. Bound states below the first ionization potential fall within the $I^a$ category and are not included. As an example of autoionizing levels ($I^b$) we give the series with 5p$^5$6sns electron configuration. Energies and state designations are from Moore's tables (Ref. 28).
results in a subsequent section. We notice in Fig. 2 that the energy range of the $I^b$ states has no upper bound. However, the probability of exciting very high-energy levels decreases rapidly with increasing binding energy.

Most of the present knowledge on auto-ionization levels and mechanisms arises from analysis of spectroscopic data, in particular the absorption measurements of Beutler and Guggenheimer in 1934,\textsuperscript{2} the spark emission measurements of Boyd in Sawyer in 1942,\textsuperscript{29} and the very recent absorption experiment of Connerade.\textsuperscript{4} In comparing the previous investigations as summarized in Moore's tables\textsuperscript{28} and Connerade's discussion,\textsuperscript{4} we have noticed several discrepancies in the assignments of $J$, $L$, and $S$ values and in level designations. There has been a change in emphasis of notation, since the early works by Beutler and Guggenheimer used $L$-$S$ coupling, whereas Connerade used the $J$-$K$ coupling scheme proposed by Racah.\textsuperscript{30} In the $L$-$S$ coupling scheme, the spin-orbit interaction is often assumed to be small compared to the Coulomb interaction, so that the orbital momentum $\ell_i$ of each electron couples strongly to each other to give $L$, and the spin $s_i$ of each electron couples to give $S$.

In Racah's method, on the other hand, an atomic system is treated as a sum of a parent ion and an external electron. The possible term values are obtained from $\hat{L}$ and $\hat{S}$, constructed by the expressions

\begin{equation}
\hat{L} = \hat{L}_p + \hat{\ell}_e ,
\end{equation}

\begin{equation}
\hat{S} = \hat{s}_p + \hat{s}_e ,
\end{equation}

where subscripts p and e stand for parent ion and external electron. Since the excited electron is in an outer shell, its electrostatic
interaction with the parent ion is weaker than the spin-orbit interaction of the parent ion. Furthermore, the electrostatic interaction of the excited electron is stronger than the spin-orbit interaction between the excited electron and the parent ion. The quantum number $\hat{J}$, as defined by Racah, is

$$\hat{J} = \hat{K} + \hat{s}_e ,$$  \hspace{1cm} (3)

where

$$\hat{K} = \hat{J}_p + \hat{s}_e$$  \hspace{1cm} (4)

and $\hat{J}_p$ is the angular momentum of the parent ion.

One of the most successful methods in calculating energies and transition rates is the close-coupling approximation\textsuperscript{31} which utilizes the eigenvalue expansion of the total wave function for the system, thereby generating second-order differential equations describing the auto-ionizing electrons. Auto-ionization has also been treated as a scattering problem\textsuperscript{32} or as a resonance effect.\textsuperscript{33} These approaches have been successful in dealing with simpler atomic or molecular systems, and expansion to more complex systems is presently being attempted by several workers.\textsuperscript{34} In view of the relevance of auto-ionization in astrophysics and atomic structure, both theoretical and experimental advancements seem to be tentative and incomplete. The results obtained during this investigation constitute a first attempt to excite the previously known doublet states by electron impact and to supplement information on the quartet states studied by Feldman and Novick.\textsuperscript{5}
FIG. 3. Apparatus. The principle of the RPD electron gun and trapped-electron collision chamber is illustrated by the schematic potential diagram. The aperture in the retarding electrode was 0.5 mm diam. Characteristic dimensions for the collision chamber are total length of 30 mm and radii of 8 and 6 mm for the cylindrical collector and grid generating surface, respectively. Both the electron-beam current $I_B$ and the trapped-electron current $I_S$ were measured with Keithley 610B electrometers. The total energy of the beam electrons in the collision region is determined by the sum of the accelerating voltage $V_a$ and the well depth $W$. 
FIG. 3
III. EXPERIMENTAL ARRANGEMENT

The well-known techniques of the RPD electron gun and trapped-electron cylindrical collision chamber were used in this investigation. The major features are as follows: The low-energy portion of the electrons pulled out from the indirectly heated cathode in Fig. 3 was retarded and cut off by the slightly negative potential at the small-aperture electrode marked R. The dc potential at this electrode was superimposed by a small ac signal with amplitude 0.12 V peak to peak and frequency (f) 29 Hz. By using phase-sensitive detection one can measure a transmitted or scattered electron current within a narrow energy interval determined by the peak-to-peak sinusoidal voltage applied to the retarding electrode. Typical beam currents were of the order of $10^{-8}$ A. An axial magnetic field was used to guide the electron beam; the magnitude of this field will be discussed later.

The principle of Schulz's trapped-electron method is to perturb the potential along the axis of the cylindrical collision region by applying a potential difference between the grid and the surrounding cylindrical collector. This leads to the following two effects:

(i) The energy of the beam electrons in the collision region is determined by the sum of the accelerating voltage $V_a$ and the well depth $W$.

(ii) Inelastically scattered electrons will be trapped in the well if their energy after collision is less than $W$. They arrive at the collector by diffusing against the radial electric field. As a result, the trapped-electron current will increase and exhibit sharp maxima when the incident electron energy approaches the energy of
bound atomic states. (Notice that the electrons that did not suffer collisions are transmitted to and collected at the beam collector to the right in Fig. 3.) The width of the trapped-electron current peaks is approximately equal to $[W^2 + (\Delta E)^2]^{1/2}$, where $W$ is the well depth and $\Delta E$ is the energy spread in the electron beam. The width given by the above expression is entirely due to the experimental method used. A wide peak would also appear if the lifetime of a state is very short. In practice, the well depth was determined by applying a negative voltage to the cylindrical detector and observing the subsequent shift in the electron-beam retarding curve, as discussed by Burrow and Schulz.\textsuperscript{36}

The average time $T_d$ it takes for the scattered electrons to diffuse out past the grid wires is given by the expression\textsuperscript{27}

$$T_d = 0.26eb^2R^2/(mv_cV) ,$$

(5)

where $e$ and $m$ are the electronic charge and mass, respectively, $B$ is the axial magnetic field in Wb/m\textsuperscript{2}, $R$ is the distance from the tube axis to the grid wires, and $v_c$ is the collision frequency for the slow electrons of energy $V$(volts). In order not to lose phase information, we require that the diffusion time be less than the inverse of the modulation frequency ($T_d < 1/f$). A too long diffusion time leads to an increase in space charge, which subsequently tends to broaden the energy resolution of the apparatus. However, this effect was not observed with total beam currents of about $10^{-8}$ A and magnetic fields of about 100 G. The magnetic field must be sufficiently large to prevent elastically scattered electrons and fast electrons generated in the auto-ionization process from reaching the cylindrical
collector. The radius of gyration for a 10 eV transverse electron electron is 0.8 mm at 130 G. The major portion of the fast electrons will, therefore, by collected at, or go through, the large-aperture holes in the end plates of the collision chamber. For the reasons discussed here the apparatus was operated with magnetic fields between 100 and 130 G.

The energy scale was calibrated by comparison with known atomic structures, notably the excitation of the $6^2p_{3/2}$ state at 1.41 eV, the first ionization potential at 3.89 eV, and the auto-ionizing $^2p_{3/2,1/2}$ states at 12.3 and 13.5 eV, all in cesium. Additional information was obtained by admitting helium to the cesium-filled apparatus and measuring the He resonance at 19.3 eV. The consistency of the energy scale thus obtained is within ±0.03 eV.

A spread in electron-beam energy arises from thermal spread of electrons leaving the cathode surface and from possible nonuniform distribution of contact potentials on electrode surfaces. Part of the thermal spread is discriminated against by the retarding potential at the small-aperture electrode in the electron gun. Since a metal surface in thermal equilibrium with cesium vapor is constantly replenished with cesium atoms, we have reasons to believe that differences in contact potential are essentially eliminated. The same observation has been made by Bullis. Disadvantages from the cesium coating show up as leakage resistances on all ceramic insulators in the apparatus. This effect was minimized by operating the apparatus, except for the cesium reservoir, at an elevated temperature of 100°C. The background pressure at that temperature was maintained by an ion pump to better than $10^{-8}$ Torr.
FIG. 4. Trapped-electron current (in arbitrary units) as a function of electron energy. The vertical arrows on the energy scale define levels compiled in Table I.
FIG. 4
The objective of this work has been to study auto-ionization levels by electron impact, and not necessarily to determine absolute excitation cross sections. For this reason we did not observe the complete set of consistency checks suggested by Kieffer and Dunn, but restricted ourselves to tests on the proportionality between the trapped-electron current and the product of beam current and cesium density. These tests were satisfied to within ±10%.

IV. RESULTS AND DISCUSSION

It is important to realize that the trapped-electron method is capable of exciting and detecting both doublet and quartet states of an atomic system. This is an advantage over spectroscopic absorption measurements which are more or less confined to doublet states.

The contribution of the faster electrons in the electron beam tends to shift the "onsets" toward a slightly lower value by an amount equal to the spread in energy. Since the energy spread was shown to be constant over the operating energy range, its effect to each onset should be the same. On this background, we have chosen the "onsets," or characteristic breaks in curvature, as a measure of the threshold energy of the $I^b$ levels. With threshold energy here we mean the onset of a new channel. With this procedure we were able to distinguish adjacent levels separated by about one-half the estimated experimental resolution.

Figure 4 shows the trapped-electron current as a function of energy in cesium vapor at $10^{-6}$ Torr. Most of the structure is due to auto-ionization states in Cs I in the energy range between 12 and 20 eV. The data analysis is reviewed in Table I, which contains
## TABLE I. Auto-ionizing levels in cesium.

<table>
<thead>
<tr>
<th>Electron impact E(eV)</th>
<th>E(eV)</th>
<th>Limit</th>
<th>Assignment</th>
<th>Moore Assignment</th>
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<tr>
<td>12.30</td>
<td>12.30</td>
<td></td>
<td></td>
<td>5p⁵6s²²p³/₂³/₂</td>
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<tr>
<td>12.80</td>
<td>12.60</td>
<td>±0.3d</td>
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<td>5p⁵6s7s⁴p</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>5p⁵6s5d⁴p</td>
</tr>
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<td></td>
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<td></td>
<td>5p⁵6s4f⁴G</td>
</tr>
<tr>
<td>13.50</td>
<td></td>
<td></td>
<td>13.52</td>
<td>5p⁵6s²²p₃/₂½</td>
</tr>
<tr>
<td>13.60</td>
<td></td>
<td></td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>14.90</td>
<td>14.924</td>
<td>12₂</td>
<td>Cs II 5p⁵5d</td>
<td>14.924</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>5p⁵6s5d, 5°(3/2)</td>
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<tr>
<td>15.35</td>
<td>15.320</td>
<td>15₂</td>
<td>Cs II 5p⁵5d</td>
<td>15.310</td>
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<tr>
<td>15.310</td>
<td>3₂</td>
<td>5p⁵6s5d</td>
<td></td>
<td>15.310</td>
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<tr>
<td>Electron impact E(eV)</td>
<td>Connerade&lt;sup&gt;a&lt;/sup&gt; E(eV)&lt;sup&gt;c&lt;/sup&gt; Limit</td>
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<td>Moore&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Assignment</td>
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<td>-----------------------</td>
<td>---------------------------------------------</td>
<td>------------</td>
<td>----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>15.70 15.680</td>
<td>12&lt;sub&gt;2&lt;/sub&gt; 5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;7&lt;/sup&gt;s[2]&lt;sub&gt;3/2&lt;/sub&gt;</td>
<td>15.680</td>
<td>5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;6&lt;/sup&gt;d, 9°(1/2,3/2)</td>
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<tr>
<td>15.670</td>
<td>7&lt;sub&gt;1&lt;/sub&gt; 5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;5&lt;/sup&gt;d</td>
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<td>16.40 16.390</td>
<td>6&lt;sub&gt;2&lt;/sub&gt; 5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;6&lt;/sup&gt;d</td>
<td>16.43</td>
<td>5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;7&lt;/sup&gt;d, 15°(1/2,3/2)</td>
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<td>16.420</td>
<td>3&lt;sub&gt;2&lt;/sub&gt; 5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;9&lt;/sup&gt;s</td>
<td>16.45</td>
<td>5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;7&lt;/sup&gt;d, 16°(1/2,3/2)</td>
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<tr>
<td>16.50 16.500</td>
<td>?  ?</td>
<td>16.45</td>
<td>5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;7&lt;/sup&gt;d, 16°(1/2,3/2)</td>
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<tr>
<td>16.510 16.952</td>
<td>6&lt;sub&gt;2&lt;/sub&gt; 5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;9&lt;/sup&gt;s</td>
<td>16.56</td>
<td>5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;9&lt;/sup&gt;s&lt;sup&gt;2&lt;/sup&gt;&lt;sub&gt;p&lt;sup&gt;3/2&lt;/sup&gt;&lt;/sub&gt;)</td>
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<tr>
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<td>7&lt;sub&gt;1&lt;/sub&gt; 5p&lt;sup&gt;5&lt;/sup&gt;6s&lt;sup&gt;7&lt;/sup&gt;d</td>
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<td>Electron impact E(eV)</td>
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$^a$Reference 4.
$^b$Reference 28.
$^c$The original cm$^{-1}$ unit has been converted to eV for easier comparison.
$^d$Reference 5.
$^e$Connerade has observed about 13 levels between 17.5 and 17.55 eV.
information pertaining to threshold energies and assignments according to Beutler and Guggenheimer,² Moore,²⁸ and Connerade.⁴

In the first column in Table I are shown the energy values in eV as observed with our trapped-electron apparatus. Our values agree with spectroscopic data (columns 2 and 5) to within the resolving power of our apparatus. The spectroscopic resolution is, of course, superior to that attainable with electron monochromators. In columns 3 and 4 are depicted the series limits to which a particular line converges, as well as the electron configuration and K, J values suggested by Connerade. (The series limits in column 3 are the levels in Cs II.) Finally, in column 5 and 6 are shown the energy values, electron configurations, and level assignments of Moore.

A critical evaluation of Table I reveals a significant discrepancy with respect to configurations and level assignments. The discrepancy is due to difficulties in assigning the observed lines to any particular series because of the complexity of the spectrum. In the energy range between 15 and 18 eV, there are many possible configurations for each observed value in column 1.

In addition to the identified doublet levels included in Table I, we have consistently observed an onset at 12.8 eV, which coincides with the quartet states reported by Feldman and Novick⁵ at 12.6 ± 0.3 eV. Our results offer a more accurate value for the onset of the quartet structure to within ±0.05 eV of 12.8 eV. We have not been able to identify the level or group of levels that appears at 20.55 eV.

To demonstrate the complexity of the auto-ionizing spectrum, we have displayed the levels of Table I in Fig. 5. Since the number of
FIG. 5. Organization of levels within known spectroscopic series. The series limits on top of the illustration are from Wheatley and Sawyer (Ref. 41). Four of the levels have been listed in two different series; they are connected with broken lines if not immediately adjacent.
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FIG. 5
of states observed by means of electron impact is much less than that observed by spectroscopic techniques, we do not have sufficient information to construct sets of Rydberg-type series, but only to invoke certain trends. Described in Fig. 5 are the observed levels arranged in terms of their energies and limits to which they may belong. The limits and the assignments are proposed by Connerade, except the 6s6s(2P_{3/2,1/2}) and 6s7s(^4F) states which can only be referenced to Moore's table and Feldman and Novick's work, respectively. Due to the uncertainties in assignments, four levels at 15.70, 16.40, 18.15, and 20.30 eV have been listed under different limits according to their possible assignment, and are connected with broken lines. In the last column are three unidentified levels "?" at 13.60, 17.95, and 20.55 eV; the middle one may possibly coincide with the 5p^56s8s(^4P^o_{1/2}) state reported by Moore.

Not included in this report is a large number of very sharp structures appearing between 20 and 30 eV, most likely due to the excitation of Cs II levels. We should also mention that we have observed bound levels around 50 eV, which might be caused by excitation of inner-core (5s) electrons.

One of the most pronounced difficulties in the analysis of spectroscopic absorption measurements is to assign the lines to particular series and from this to deduct the corresponding effective quantum numbers. The appearance of sharp and diffuse lines, for instance, presents itself as a valuable guide. By studying the scattering of electrons in the forward direction in an electron monochrometer-analyzer system we hope to develop quantitative procedures that will supplement the spectroscopic techniques, thereby obtaining
more information on the high-energy structure of atomic and molecular systems. In particular, the oscillator strength for the doublet states can be determined by this method.

V. REFERENCES

1 Most of the references in this paper pertain to cesium and the other alkali metals. A more general review is found in Autoionization, Astrophysical, Theoretical, and Laboratory Experimental Aspects, edited by A. Temkin (Mono Book Co., Baltimore, 1966).


3 G. V. Marr, Photoionization Processes in Gases (Academic, New York, 1967), pp. 132-156. (Marr's measurements in cesium extend only to 10 eV, which is below the first auto-ionization level at 12.3 eV.)


12 See article by A. Burgess, Ref. 1, pp. 25-31.

13 See article by L. Goldberg, Ref. 1, pp. 1-23.


24. Following Beutler and Guggenheimer (Ref. 2) we are using the general notation $I^B$ for bound states above the first ionization potential.
26. We have compiled an annotated bibliography (unpublished) containing about 85 references on the RPD gun. Interested readers may request copies.
35. The electron currents were measured with a Keithley 610B electrometer and a PAR HR-8 lock-in amplifier.


39 The vapor pressure was determined from the formula of I. Langmuir and J. B. Taylor, Phys. Rev. 51, 753 (1937).


41 M. A. Wheatley and R. A. Sawyer, Phys. Rev. 61, 591 (1942).
PART B

EXCITATION OF 5p-ELECTRONS IN CESIUM

BY ELECTRON IMPACT

(To be submitted to the Physical Review)
ABSTRACT

Excitation of 5p-Electrons in Cesium by Electron Impact

The structure in the electron impact ionization cross section in cesium can be partially accounted for by the mechanisms of autoionization and excitation-ionization of 5p-electrons. For electron energies above 17 eV a large fraction of the ions are metastable and can be detected by Auger emission from a metal surface. The experiment was performed in a crossed cesium atom-electron beam apparatus, and the metastable ions were counted with a channel electron multiplier. The metastable ion count rate was a factor of 100 higher than that due to photons from atomic and ionic transitions. We have measured the overall excitation function for a number of Cs+ metastable levels, the lowest being 5d{[3 l/2], 3} at 17.02 eV and 5d{[1/2], 1} at 17.06 eV.

In addition, by retarding the ions before they reach the Channeltron, the apparatus was made selectively sensitive to vuv photons. The lowest ionic level excited was 5p^56s{[1 l/2], 1}, resulting in photon emission at 926.75 Å.
I. INTRODUCTION

In recent years technological developments in the fields of plasma physics,\(^1\) astrophysics,\(^2\) laser physics,\(^3\) and energy conversion devices\(^4\) have resulted in a number of investigations of the ionization cross section for cesium.\(^5-10\) Figure 1 is a summary of reported Cs ionization cross sections by electron impact. In all of the curves, we notice a sharp onset at 3.9 eV followed by two maxima around 15 and 28 eV. The initial onset is due to the removal of 6s-valence electrons in a direct impact, i.e.,

\[ \text{Cs}(5p^66s) + e \rightarrow \text{Cs}^+(5p^6) + 2e \]  

(1)

The structure peaked around 15 eV is a result of autoionization in Cs. We have previously reported on the significance of autoionization in the total ionization cross section of cesium,\(^11\) which results from excitation of a 5p-electrons followed by electron emission in a nonradiative transition. A typical example discussed in our earlier paper is

\[ \text{Cs}(5p^66s) + e \rightarrow \text{Cs}^*(5p^56s^2) + e \]
\[ \rightarrow \text{Cs}^+(5p^6) + e + e(\text{Auger}) \]  

(2)

In reaction (2) the ejected Auger electron carries off the excess energy from the doubly excited state. The lifetime of the intermediate excited state \(\text{Cs}^*\) may be as short as \(10^{-14}\) sec or as long as \(10^{-4}\) sec.\(^12\)

The broad maximum around 28 eV has been attributed to removal of inner-shell electrons by mechanisms different from autoionization.\(^5,8-11\) The objective of the present paper has been to study the
FIG. 1. Compilation of cross-section data for production of Cs$^+$ ions from cesium by electron impact. \( \text{H + S: Heil and Scott (Ref. 7)}; \text{K + P: Korchevoi and Przonski (Ref. 8)}; \text{T + S: Relative measurements of Tate and Smith (Ref. 22) normalized to the absolute measurements of Nygaard (Ref. 10)}; \text{N: Nygaard (Ref. 10)}; \text{Z + A: Zapesochnyi and Aleksakhin (Ref. 9)}; \text{□: Brink (Ref. 34)}; \text{●: McFarland and Kinney (Ref. 5)}; \text{○: McFarland (Ref. 6)} \)
additional ionization mechanisms which include direct excitation-ionization of inner-shell electrons leading to production of metastable or short-lived excited cesium ions. The generation of metastable ions by electron impact of ground state atoms is exemplified in

\[ \text{Cs}(5p^66s) + e \rightarrow (\text{Cs}^+)^m + 2e, \]  

(3)

where \( m \) symbolizes a metastable species. Another possibility is the excitation of a short-lived excited ion, i.e.,

\[ \text{Cs}(5p^66s) + e \rightarrow (\text{Cs}^+)^* + 2e, \]  

(4)

where the reaction product will decay by photon emission to lower states, which may include the metastable states discussed above.

The apparatus used in this investigation consists of a Cs atomic beam intersected at 90 degrees by an electron beam and a channel electron multiplier (Channeltron)\(^{13}\) for detecting ions and emitted photons. With a retarding electric field in front of the Channeltron only photons would be detected. Since the Channeltron counting efficiency was found to be much higher for the metastable ions than for ground state ions or photons, the lowest metastable level could be easily identified. The higher detection efficiency for the metastable ions is mainly due to the higher secondary electron emission efficiency for the metastables. The electron energy range studied was from 3-45 eV, and the energy resolution of the electron beam was about 0.2 eV.

In the following sections of this paper we discuss the energy levels of Cs II and describe the apparatus used to excite and detect the ionic levels. The results in the form of ion and photon count rates are discussed separately. The lowest metastable states observed were \( 5d_{3/2}, 3 \) at 17.02 eV and \( 5d_{1/2}, 1 \) at 17.06 eV, and the
lowest photon-emitting state (926.75 A) was 6s[1 1/2], 1) at 17.27 eV.

II. Cs II ENERGY LEVELS

Energy levels of Cs II were first studied by Wheatley and Sawyer\textsuperscript{14} using a spark spectrograph and many of the lines were classified. The results of this and some of the later studies have been summarized by Moore.\textsuperscript{15} To our knowledge, the life times of the resonance lines in Cs II have not been reported in the literature. However, the corresponding lines in Xe I are known to be of the order of $10^{-8}$ sec.\textsuperscript{16} Another method yielding information on the resonance lines of Cs II has been to slow down fast cesium ions in targets of He, Ne, and Ar.\textsuperscript{17-19} The present paper represents a first attempt to study excited cesium ions produced by electron impact of ground state cesium atoms.

In Fig. 2 are shown some of the lower excited states of the Cs\textsuperscript{+} ion.\textsuperscript{20} The numbers following the electron configuration of each level are [K]- and $J$-values of the respective state. According to the Racah scheme\textsuperscript{21} for electron coupling,

$$
\vec{J} = \vec{J}_p + \vec{J}_e ,
$$

and

$$
\vec{J} = \vec{K} + \vec{s}_e ,
$$

where $\vec{J}_p$ is the total angular momentum of the core, and $\vec{s}_e$ and $\vec{s}_e$ are the orbital and spin angular momentum of the external electron, respectively. Because of the complexity of the Cs II structure, the simplified $(L,S)$ and $(j,j)$ coupling schemes are inaccurate.
FIG. 2. Simplified Cs II term diagram. All of the lower-lying levels between 3.89 and 21 eV are included. The arrows indicate resonance transitions with respective wave lengths.
Consequently, the Racah notation has been exclusively used in this work and the J-value for each state has been given instead of the common L- and S-values. In general, the highest and the lowest values of the total angular momentum, J, are identical for all electron coupling schemes. This implies that the energy levels of a complex atomic system with the highest or the lowest J-values will generally follow the same transition rules as in a simpler system. In the case of Cs\(^+\) ionic levels, it has been reported\(^{14}\) that there are no exceptions to the transition rule for J-value, namely \(\Delta J = 0\) or \(\pm 1\), except that \(J = 0\) to \(J = 0\) is forbidden.

For some of the lowest s- and d-electron configurations of the Cs\(^+\) ion we have assigned level designations according to L•S coupling, as shown in Fig. 2. Also included in Fig. 2 are strong radiative transitions and the wavelengths of the resulting photons. It should be noted that the multiplicity of a given electron configuration does not have the same meaning in a complex system as in a simpler one. For example, in the downward transitions of \(3P_1\) to the ground state of Cs\(^+\) ion, \(1S_0\), the J selection rule is obeyed but not the multiplicity rule.

III. EXPERIMENTAL ARRANGEMENT

Excited ionic states of cesium have been studied in a Tate and Smith-type\(^{22}\) total ionization apparatus modified to incorporate an atomic beam and a Channeltron (Fig. 3). The ions produced are expelled from the interaction region by a transverse electric field and counted by a Channeltron. In another mode of operation the ions are retarded,
FIG. 3. Total ionization apparatus with channel electron multiplier for detection of vuv photons and Cs$^+$ ions. The direction of the atomic beam is perpendicular to the plane of the paper. The atomic beam, electron beam, and ion extraction field are orthogonal to each other.
and photons only are detected. The directions of the electron beam, atomic beam and ion draw-out electric field constitute an orthogonal system. Magnetic fields of about 200 gauss were used to collimate the electron beam. The system background pressure was better than $5 \times 10^{-9}$ torr.

The electron gun is of the retarding potential difference (RPD) type developed by Fox et al.\textsuperscript{23} It consists of an indirectly heated cathode and five acceleration and control electrodes. Typically, the electron beam current was of the order of $10^{-7} - 10^{-8}$ A in order to avoid space charge effects. The zero point on the energy scale was found from the sharp onset of the electron beam current at low accelerating voltage and from retarding the electron beam in front of the electron collector. For sufficiently low beam currents, the zero point on the energy scale was found to be independent of the magnitude of the current. Other points on the energy scale were compared with known levels in the autoionization spectrum.\textsuperscript{9-10}

The effect of the helical path of the beam electrons in the collimating magnetic field has been discussed by Massey and Burhop.\textsuperscript{24} In the present experiment we were limited to magnetic fields below 200 gauss in order for the Channeltron to operate properly. Even under this condition the increase in path length for the beam electrons was found to be negligible. Unfortunately, for magnetic fields below 200 gauss the electron beam energy resolution was found to be about 0.2 eV, as compared to 0.1 eV at a magnetic field of 700 gauss. In all cases, the energy spread was determined from the retardation measurements discussed above.
The cesium atomic beam was formed in a linear array of parallel capillaries each of length 10 mm and inside diameter 0.12 mm. The electron beam was aligned in such a way that it was completely immersed in the atomic beam and the length of the interaction region was 25 mm. The Cs density in the collision region was from $10^{10}$ to $10^{11}$ atoms per cm$^3$. It was monitored by measuring the cesium ion current at a given electron energy and determined by means of the known absolute ionization cross section. In addition it was measured with a surface ionization detector. The result of the two methods agreed to within ±5%. The stability of the cesium beam density was excellent, typically constant to within less than 1% over a single data run lasting 100 min.

The Channeltron was located behind the ion collector plate in the collision chamber looking into a reaction region through a rectangular hole of 4 x 1 mm$^2$. The Channeltron input end was operated at a negative potential with respect to the interaction region to prevent any stray electrons from hitting it and also to accelerate ions. The background count rate for a new Channeltron was about one count per sec, increasing gradually to about 50 counts per sec after about 200 hours due to cesium exposure. An extensive study of Channeltron operating characteristics in magnetic fields has been carried out independently. It was found that the Channeltron exhibited a sufficiently high gain at 200 gauss when the applied voltage was increased to 4000 volts. For completeness, we should note that the photon counting efficiency of a Channeltron falls off very sharply for photons with wavelength above 1500 Å and becomes less than 1% above
3000 Å, thus making it solar blind. The long-term stability of the Channeltron amplification was very good as verified from the reproducibility of the data. The Channeltron pulses were amplified and analyzed in a discriminator with lower threshold adjusted to eliminate background counts in the absence of the electron beam current. In order to eliminate scattered electrons from hitting the entrance of the Channeltron, the entrance aperture was operated at a negative potential larger than the maximum electron beam energy.

IV. RESULTS AND DISCUSSION

A. Radiative Transitions

The reaction rate for the production of excited ions described by Eq. (4) can be written as

\[
\frac{dn_+^*}{dt} = - \frac{n_+^*}{\tau} + \frac{j_0}{e} n_0 \sigma_+^* \ ,
\]

where \( n_+^* \) is the number density of ions in a specific excited state with life time \( \tau \). For simplicity, we have excluded the additional contributions due to cascading from higher states. The experimental parameters in Eq. (7) are \( j_0/e \) and \( n_0 \), which represent the flux of beam electrons and the number density of ground state cesium atoms, respectively. (\( e \) is the electronic charge.) The evaluation of the cross section \( \sigma_+^* \) is rendered simple by the fact that the electron beam flux (or current \( I_+ \)) is constant to within 1% over the energy range covered in this investigation. In steady state, the average number of photons that will be detected by a Channeltron with quantum efficiency \( \eta^* \) is
\[ N^* = \frac{1}{e} n^* \Omega_{rel} I_\lambda n_0 \sigma_+^* \]  

(8)

In the experiment we measure the count rate \( N^* \), the electron beam current \( I_\lambda \), the length of the interaction region \( \lambda \), and the number density of cesium atoms \( n_0 \). The cross section could then be determined if the relative solid angle \( \Omega_{rel} \) and the quantum efficiency \( n^* \) were known. To within a factor of two, the relative solid angle, \( \Omega_{rel} \), which is defined by the slit area in the collision chamber and the area of the Channeltron entrance (see Fig. 3) equals \( 10^{-5} \). The value for the photoelectric quantum efficiency \( n^* \) for the Channeltron entrance surface, which is coated with unspecified layers of oxygen and cesium, is very uncertain. In this work, we have assumed a value of \( 10^{-2} \) in the 800-1000 Å region. With these numbers, we obtain from the results shown in Fig. 4 a maximum cross section of about \( 10^{-16} \text{ cm}^2 \) at an electron energy of 35 eV. The solid line in Fig. 4 represents an excitation curve for radiation of all wavelengths detected by the Channeltron. We note that cascading from the \((5p^56p[1 1/2], 1)\)-level and from all levels above) into the lower levels \((5p^56s[1 1/2], 2)\), \((5p^55d[1 1/2], 1)\), \((5p^56s'[1 1/2], 0)\), and \((5p^55d'[1 1/2], 1)\) lead to the emission of vuv radiation.

For comparison, we have calculated the same cross section from Gryzinski's formula: 29

\[ \sigma_i = \left( \frac{\sigma_o}{U_i^2} \right) \frac{1}{x} \left[ \frac{x-1}{x+1} \right]^{3/2} \left\{ 1 + \frac{2}{3} \left[ 1 - \frac{1}{2x} \right] \ln \left[ \frac{2.7 + (x-1)1/2}{} \right] \right\} \]  

(9)

where \( x = U/U_i \) and \( \sigma_o = 6.56 \times 10^{-14} (\text{eV}^2 \cdot \text{cm}^2) \). As a representative binding energy for the 5p-electrons we have used \( U_i = 17.2 \text{ eV} \). The
FIG. 4. Photon count rate as detected by the Channeltron vs. electron energy. An energy independent background of 30 counts per sec has been subtracted from the total rate. Ions were prevented from entering the Channeltron by a retarding electric field. The electron current was $2 \times 10^{-7}$ A and the cesium number density was $2 \times 10^{10}$ cm$^{-3}$. The theoretical curve using Gryzinski's formula (see Ref. 29) is also shown. The experimental curve is normalized to the theoretical curve at 35 eV.
result of the calculation using this semi-empirical expression is included in Fig. 4 (dotted line), in which the maximum in the experimental curve at 35 eV has been normalized to the Gryzinski theory. At that energy, the calculated cross section is $2.2 \times 10^{-16}$ cm$^2$, in reasonable agreement with our previously estimated experimental cross section. The justification for using this particular theory relies on its success in predicting the total ionization cross section for alkali elements. For example, Nygaard$^{10}$ and McFarland$^{30}$ have pointed out that the agreement between experiment and theory is within $\pm 5\%$ at maximum, although this agreement might be partly accidental.

Note that the photon count rate displayed in Fig. 4 shows an onset at 17.2 eV which is reasonably close to the lowest excited state of the ion, $5p^5 6s\{1/2, 1\}$ at 17.27 eV, leading to photon emission at 926.75 Å. Any structure in the excitation curve (Fig. 4) is not evident below 20 eV. Excitation of the $\{1/2, 1\}$ (813.85 Å), $\{1 1/2, 1\}$ (808.77 Å), and $\{1 1/2, 1\}$ (901.34 Å) levels leads to strong emission lines,$^{14,31}$ but due to a count rate of less than 4 sec$^{-1}$ for electron energies below 20 eV combined with an energy resolution of 0.2 eV, these levels were not discernible.

The zero count rate for electron energies below 17.2 eV is an interesting observation since a high number of $I_a$ atomic states are present between 1.4 eV and the first ionization potential at 3.89 eV (3184 Å). Since the Channeltron has extremely low sensitivity for wavelengths above 3000 Å, the zero count rate for energies below 3.89 appears reasonable. Another possibility for photon emission would be from the doubly excited states ($Cs I_b$) between 12.3 and 17.2 eV, as
discussed in our previous work. Our observation of a zero photon count rate in this region tends to support the hypothesis that the doubly excited cesium atomic levels decay primarily by the radiationless autoionization process.

B. Production of Metastable Ions

In the preceding section the Channeltron was made selectively sensitive to vuv photons by retarding all ions produced. On the other hand, both photons and ions would be detected if the latter are accelerated before hitting the detector. Typically, the total count rate due to photons and ions (unexcited and metastable) was a factor of 100 higher than the net photon count rate under identical experimental conditions.

In our apparatus the transit time of ions between the production region and detecting surface is about 15 μsec. Hence, excited ions with lifetime less than this value will have decayed to the ion groundstate before arriving at the detector. For comparison, it should be noted that the lifetimes of the states studied in the previous section were of the order of 10^-8 sec.16

We have been using this method to study the production of ground-state and metastable cesium ions. A characteristic observation is shown in Fig. 5. As mentioned above, the total count rate is due primarily to ions, with the photon count amounting to about 1% of the total. It is of interest here to compare ionization curves obtained by measuring the total ionization current to one of the parallel plates (similar to Tate and Smith) with an electrometer (dotted line)
FIG. 5. Cs\(^+\) ion counts vs. electron beam energy (solid line). The dotted line represents the total ion current as measured with an electrometer. The ion current rate was normalized to the total ion current at 15 eV. The electron current was \(4 \times 10^{-8}\) A and the cesium density was \(2 \times 10^{10}\) cm\(^{-3}\).
and by detecting individual ions with a Channeltron (full drawn line). These two independent measurements have been normalized to the auto-ionization peak at 15 eV, and agree with each other to within ±2% from threshold to about 17 eV. Above 17 eV the ionization curve obtained from ion counting rises above the classical current measurement. We ascribe the difference to production of metastable ions, and will in the following discuss this effect in more detail.

One of the major advantages of total ionization measurements using the method of Tate and Smith is that both groundstate and excited ions of identical charge contribute equally to the total ionization current \( I_{\text{tot}}^+ \), provided that sufficient care is taken to suppress secondary electrons. Multiply charged ions will be measured according to

\[
I_{\text{tot}}^+ = \sum_{Z=1}^{Z_{\text{max}}} Z I^Z, \tag{10}
\]

where the charge number \( Z_{\text{max}} \) depends on the energy of the bombarding electrons. Unfortunately, this is not the case in ion counting experiments since the production of secondary electrons by ion impact on a metal surface depends on both the kinetic and internal energy of the ions.

If a metastable ion hits the detecting surface it will be counted with a higher probability because of its higher value of the secondary emission coefficient \( \eta^M_+ \) as compared to the value \( \eta_+ \) for groundstate ions. Therefore, the total count rate can be written as

\[
N = n_0 \frac{I}{e} \ G \left[ \eta_+ \sigma_+ + \eta^M_+ \sigma^M_+ + \eta_{++} \sigma_{++} \right]. \tag{11}
\]
where \( G \) is a known geometrical factor common for both groundstate and metastable ions, and \( \sigma_+ \) and \( \sigma^M_+ \) are the corresponding cross sections for production of these species. The last term in Eq. (11), \( n_+ \sigma_+ \), describes the production and detection of Cs ions above the ionization threshold at 29 eV. We have neglected the contribution due to photons as justified earlier.

By taking the difference between the normalized count rate and ion current measurements we obtain information on the excitation curve for production of metastable ions. The result of this procedure is shown in Fig. 6, and represents the sum of direct excitation and cascading into the lower metastable levels. The very sharp "onset" at 17 eV is in excellent agreement with the energy of the lowest metastable states of Cs\(^+\), \( 5p^55d\{[3 \, l/2, \, 3] \) at 17.02 eV and \( 5p^55d\{[1/2, \, 1] \) at 17.06 eV. The general shape of the excitation curve (Fig. 6) resembles closely that of triplet excitation curves,\(^{32}\) although one has to be very careful distinguishing between singlet and triplet series in the complex Cs\(^+\) system.

By comparing the ion count to the ion current measurements for energies below 17 eV, the product \( G n_+ \), which enters in Eq. (11), can be determined. In principle, an absolute magnitude could be assigned to the excitation curve in Fig. 6 if the ratio \( n^M_+/n_+ \) were known. If we estimate \( \sigma^M_+ \) to be of the order of \( 10^{-16} \) cm\(^2\) and \( \sigma^+_+ \approx 10^{-15} \) cm\(^2\) (Ref. 10), we obtain \( n^M_+/n_+ \approx 10 \). One reason for the apparently high value of \( n^M_+ \) might be that excitational energy is transferred more efficiently to the surface than translational energy. This effect has been studied by Hagstrum\(^{33}\) for rare gas ions, both groundstate and
FIG. 6. Relative excitation cross section for metastable ion production. The curve was obtained by taking the difference between the normalized ion count rate and the total ion current in Fig. 5.
metastable, incident on clean and contaminated tungsten surfaces. The
difficulty in this kind of investigation is to detect metastable ions
in a high background of groundstate ions. However, for electron beam
energies above the onset for metastable ion production there is a pro-
nounced increase in the production of secondary electrons at the sur-
face. In fact, there is a characteristic similarity between Fig. 10
in Hagstrum's paper\(^{33}\) (100 eV Xe ions incident on contaminated tung-
sten) and Fig. 6 in the present paper for 250 eV Cs\(^+\) ions detected
by a contaminated Channeltron surface. The ratio of \(n_M/n_+\approx10\) for
Cs\(^+\) ions of 250 eV is therefore not surprising. It is also implied
(see Fig. 7) that for lower ion energies (\(\approx50\) eV) the signal due to
groundstate cesium ions can be suppressed as compared to the signal
due to the metastable ions.

More information about the threshold behavior for production of
metastable cesium ions is shown on an expanded energy scale in Fig. 7.
The major difference between Fig. 5 and Fig. 7 is that an ion energy
of 50 eV was used in the latter observation, thus decreasing the
probability for detection of groundstate ions. The mean standard
deviation in the count rate was about 1 count per sec. Several of
the discontinuities in the curve may be due to the resonance or an
opening of a new channel. With the exclusion of levels decaying by
resonance radiation, the levels are the same as those in Fig. 2. Note
that cascading from levels above 19 eV represents an additional
mechanism for production of metastable ions. The detector is insensi-
tive to the cascading radiation, which was demonstrated by retarding
all ions in front of the detector.
FIG. 7. Cs$^+$ ion counts vs. electron energy near threshold. Vertical lines are the levels of Cs II. The four levels decaying by emission of resonance radiation (see Fig. 2) are not included. Excited states above 19.5 eV decay to one of the lower states henceforth producing either vuv photons or metastable ions.
In concluding this section, we want to point out that the metastable ion excitation curve obtained in the course of this study constitutes an additional mechanism for explaining the structure in the \( \text{Cs}^+ \) ionization cross section around 28 eV. This observation, combined with the emission of vuv photons and the process of autoionization, have shed new light on the overall structure in the \( \text{Cs}^+ \) cross section.

C. Consistency Checks

In both the photon and ion counting experiments the following consistency checks were conducted:

(i) The count rates corrected for background were found to be proportional to the electron beam current from \( 2 \times 10^{-8} \) to \( 5 \times 10^{-7} \) A. For currents below \( 5 \times 10^{-7} \) A the electron beam current was independent (to within \( \pm 1 \% \)) of the electron energy up to about 50 eV.

(ii) The count rates were proportional to the atomic beam density from \( 10^{10} \) to \( 10^{11} \) cm\(^{-3} \).

Since the absolute sensitivity of the detector with respect to photons and ions was not known, only relative cross sections could be obtained in this work.

V. CONCLUSIONS

The following conclusions related to the production of \( \text{Cs}^+ \) ions by electron impact and to ion counting techniques in general can be drawn from our observations:

(i) The excitation of short-lived excited states of \( \text{Cs}^+ \) accounts partly for the broad maximum seen on the \( \text{Cs}^+ \) ionization cross section curve
around 28 eV. At that energy, the cross section for production of excited ions is about $10^{-16}$ cm$^2$, which agrees within an order of magnitude with the result of a Gryzinski calculation for ionization of 5p-electrons. The lowest level excited was $5p^56s\{1\ 1/2, 1\}$ at an energy of 17.27 eV above the groundstate of CsI.

(ii) In addition to the short-lived states of CsII we also detected metastable states with lifetimes in excess of 15 µsec. The lowest metastable states in CsII are $5p^55d\{8\ 1/2, 3\}$ at 17.02 eV and $5p^55d\{1/2, 1\}$ at 17.06 eV. Within the limits of the experimental resolution and accuracy of the energy scale, a positive identification of the lowest level could not be made. The overall excitation function for production of metastable ions was measured. The cross section for production of metastables is of the same order of magnitude as the cross section for production of short-lived ionic excited states. The two mechanisms combined provide a reasonable explanation for the second maximum on the ionization curve.

(iii) Total ionization cross sections obtained from the measurement of ion currents are in general considered to be more reliable than ion counting measurements if ion counter is not operated at high efficiency, since the secondary electron coefficient due to excited ions is much higher than that due to groundstate ions. Our general observation in Cs$^+$ also applies to other atomic systems. Therefore, great care should be exercised when analyzing the data of ion counting experiments for the purpose of obtaining absolute cross sections.
VI. REFERENCES


In addition to the levels shown in Fig. 2 the following states may be excited for electron energies above 19.5 eV: There are four 5p^56p'-levels around 22 eV, eight 5p^56d and 5p^57s-levels around 23 eV, six 5p^57p-levels around 23.5 eV, and over fifty spectroscopically identified 5p^5ns-, 5p^5np-, and 5p^5nd-levels between 23.5 and 25 eV. These levels decay by photon emission to the levels shown in Fig. 2, obeying the transition rules discussed in the text.

G. Racah, Phys. Rev. 61, 537 (1942).


APPENDIX

CHANNELTRON GAIN IN MAGNETIC FIELDS

(Part of this material will be published in the Review of Scientific Instruments)
ABSTRACT

CHANNELTRON GAIN IN MAGNETIC FIELDS

The gain and total count rate of electron channel multipliers depend strongly on applied magnetic fields. We report experimental results for Channeltrons operated in magnetic fields of up to 300 Gauss, and find that the applied voltage must be increased to about 4000 volts to maintain a sufficiently high gain. Slightly higher count rates are observed if the magnetic field is parallel to the plane of the Channeltron, as compared to perpendicular to that plane.
INTRODUCTION

Channel electron multipliers have been used with great success for detection of electrons, ions, metastable and fast ground-state atoms, vuv photons, and γ-rays. The low background count rate, high gain, and reasonably narrow pulse height distribution are all properly documented in the literature. Unfortunately, difficulties arise when these detectors are located inside the magnetic fields required in a number of atomic and nuclear physics experiments.

The objective of the present work has been to study the operation of channel electron multipliers in magnetic fields up to 300 Gauss by measuring pulse height distributions and total count rates as functions of applied voltage and magnetic field.

Most of the results obtained are, for practical and economical reasons, presented graphically. The data are discussed and conclusions and recommendations are made in the last part of the paper.

EXPERIMENT

The investigation was done with a Bendix Channeltron Model 4010, whose curved channel extends through an arc of 270°. Since the channel itself lies completely in one plane, an external magnetic field either parallel to or perpendicular to that plane can be easily arranged.

The Channeltron was mounted in a vacuum chamber with pressure well below 10⁻⁷ Torr, and the magnetic field, uniform to within ±5%, was produced by an external magnet. The two different orientations
were obtained by rotating the vacuum chamber through an angle of 90°. In the following, we shall define \( B_\perp \) as the case where the magnetic field is perpendicular to the plane of the Channeltron, as described above, and \( B_\parallel \) as the magnetic field parallel to that plane. In the case of \( B_\parallel \) we have not noticed any differences in the gain of the Channeltron at different rotations.

The potential difference between the electron collector and the end of the channel was 10% of the total applied voltage. The electron pulses at the collector were amplified with a Nuclear Data PAD ND 520, and eventually analyzed with a Nuclear Data Multichannel Analyzer Model 2200. The lower discriminator was set at a level to eliminate amplifier noise when the radioactive source \(^{57}\text{Co}\) was removed. In most cases the radioactive source was outside the vacuum chamber. Count rates of the order of 10-1000 per sec were obtained by using sources of different activities and by shielding. Fatigue effects due to count rates in the excess of \(10^4\) per sec\(^4\) were generally avoided.

The major difficulty that arises when an electron channel multiplier is immersed in a magnetic field is the finite radius of gyration of the electrons which decreases their kinetic energy at impact, leading to a reduction in the effective secondary emission coefficient. The accompanying macroscopic effects such as pulse height distribution and count rate are illustrative of the loss of gain in the device, as exemplified in the following section.

RESULTS AND DISCUSSION

When an electron channel multiplier is exposed to the radiation from an external radioactive \(\gamma\)-source, photoelectrons will be produced
FIG. 1. Relative pulse height distributions for Channeltron at zero and 72 Gauss. The applied voltage was 3200 volts. The large number of small amplitude pulses is due to avalanches starting downstream from the channel entrance.
FIG. 1

Relative Pulse Height

Count Rate (Arbitrary Units)

72 Gauss

0 Gauss

FIG. 1
along the total length of the tube as well as from the surrounding vacuum walls and mounting fixtures. By maintaining the potential at the channel entrance sufficiently negative with respect to the grounded surroundings, only the flux of electrons produced at the Channeltron entrance will contribute to the total count rate. It is important here to realize that the electron avalanches initiated at the opening itself propagate a longer distance than those being initiated inside the tube. Therefore, photoelectrons produced at the entrance lead to a well defined peak in the pulse height distribution, as shown in Fig. 1. The distribution of low-energy pulses is accounted for by avalanches starting elsewhere in the channel. The peak pulse amplitude, as defined in Fig. 1, is a function of magnetic field and is clearly displaced to the left when the magnetic field is increased from 0 to 72 Gauss. If the peak pulse height is plotted vs. magnetic field, as shown in Fig. 2, it will first pass through a maximum, and then apparently decrease linearly with B for values above 40-50 Gauss. This effect occurs with magnetic field perpendicular or parallel to the plane of the Channeltron.\textsuperscript{16}

As the gain of the Channeltron decreases, the total count rate will also decrease. We are in a fortunate position here to make comparison with the data of Barnett and Ray,\textsuperscript{13} who made similar measurements on a tube from Mullard (Model B 419 BL). The results are compiled in Figs. 3 and 4, with magnetic field parallel and perpendicular to the channel plane, respectively. When comparing the results from the two devices one should keep in mind that their geometries are not identical. Barnett and Ray found a pronounced difference in
FIG. 2. The peak pulse height as obtained from pulse height distributions plotted as a function of magnetic field. The applied voltage was 3200 volts.
FIG. 3. Total count rate as a function of magnetic field applied parallel to the plane of the Channeltron with applied voltages of 3000, 3500, and 4000 volts. The broken line refers to the work of Barnett and Ray (Ref. 12) using a Model B 419 BL Mullard channel electron multiplier. For comparison their results are normalized to the present data at 3000 volts and zero magnetic field.
FIG. 4. Same as in Fig. 3, but with the magnetic field perpendicular to the plane of the Channeltron.
count rate between the $B_{||}$ and $B_{\perp}$ cases, the former being the most favorable for magnetic fields up to 120 Gauss.

In the present work we find that Channeltrons can be operated in a magnetic field environment ($B_{||}$) of up to 300 Gauss if the applied voltage is increased to 4000 volts. Of this, 3600 volts are across the channel itself, approaching the maximum of 4000 volts recommended by the manufacturer. The functional dependence of count rate vs. magnetic field appears to be the same for $B_{\perp}$ and $B_{||}$, although the latter orientation yields a higher count rate for applied voltages of 3500 and 4000 volts.

The results obtained in this study are applicable not only to the detection of $\gamma$-rays, but also to mass spectrometers, electron guns, and other experiments where $\mu$-metal shielding of the Channeltron is impractical.
REFERENCES

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16Computation based on a trajectory theory are in progress in our laboratory. The results will be reported in a separate study.
VITA

Yu Bong Hahn was born on October 26, 1942, in Seoul, Korea. He received his primary and secondary education in Seoul, Korea. He has received his college education from West Virginia Wesleyan College, Buckhannon, West Virginia, and received a Bachelor of Science in Physics. He has been enrolled in the Graduate School of the University of Missouri-Rolla since September 1966. In February 1968 he was awarded the degree of Master of Science in Physics.