01 Jan 1975

Photoionization Of The 6P32,122 Fine-structure Levels In Cesium

Kaare J. Nygaard
Missouri University of Science and Technology

Robert E. Hebner

James A. Jones
Missouri University of Science and Technology

Robert J. Corbin

Recommended Citation

K. J. Nygaard et al., "Photoionization Of The 6P32,122 Fine-structure Levels In Cesium," *Physical Review A*, vol. 12, no. 4, pp. 1440 - 1447, American Physical Society, Jan 1975.
The definitive version is available at https://doi.org/10.1103/PhysRevA.12.1440

Photoionization of the $6^2P_{3/2,1/2}$ fine-structure levels in cesium*

Kaare J. Nygaard
Department of Physics, University of Missouri–Rolla, Rolla, Missouri 65401†
and FOM–Institute for Atomic and Molecular Physics, Kruislaan 407, Amsterdam, The Netherlands

Robert E. Hebner, Jr.,‡ J. Daniel Jones,§ and Robert J. Corbin
Department of Physics, University of Missouri–Rolla, Rolla, Missouri 65401

(Received 23 June 1975)

The relative photoionization cross sections for cesium atoms selectively excited to the $6\,^2P_{3/2,1/2}$ states have been measured in a triple-crossed-beam experiment. A cesium discharge lamp produced resonant wavelengths of 8521 and 8944 Å for the excitation process. A Hg-Xe lamp combined with a grating monochromator was used for the actual ionization in the wavelength region from 2500 to 5000 Å. Background counts due to photoionization of ground-state cesium atoms and dimers as well as various surface effects were discriminated against by chopping the excitation light source. The data are compared with results from radiative-recombination measurements in which the fine-structure levels are not resolved and with recent model-potential calculations. The wavelength (λ) dependence of the cross section indicates a λ^2 dependence at threshold ($\approx$5000 Å) and a λ^4 behavior at lower wavelengths.

I. INTRODUCTION

The present study is designed to determine the wavelength dependence of the photoionization cross section of cesium from the first excited state. Cesium is used extensively in many plasma devices such as thermionic energy converters, ion and plasma propulsion engines, MHD generators, and lasers. In many of these applications high densities of excited atoms can occur, and these atoms can be ionized by electron impact or by photoabsorption. Since the maximum cross section for photoionization of the $6\,^2P$ states in cesium is reported to be two orders of magnitude larger than the maximum for the ground state,[1-5] this process could contribute significantly to the over-all ionization rate.

Although there is general agreement between experiment and theory as to the absolute value of the photoionization cross section at threshold, there is disagreement over the variation of this cross section with wavelength and some question as to the reliability of the earlier experiments. Another reason to perform this study is to establish a general procedure for determining two-step photoionization cross sections, since this process is being used in such practical applications as isotope separation.[6] It has also been suggested[7] to produce polarized electrons by photoionization of oriented excited cesium atoms, and experiments along these lines are presently in progress.[8]

Related work on photoionization of metastable He and Ar atoms has been performed by Stebbings *et al.*[9] Gallagher and York[10] have studied photoionization of metastable barium for the purpose of producing nearly monoenergetic electrons, and Bradley *et al.*[11] have investigated autoionization of Ba and Mg in the ^1P states.

The simplified term diagram shown in Fig. 1 depicts the wavelengths needed for excitation to and ionization from the $6\,^2P$ states in cesium. The experiment proceeds in two steps: First, the ground-state atoms are excited according to the process

$$\mathrm{Cs}(6\,^2S_{1/2}) + h\nu_0 \rightarrow \mathrm{Cs}^*(6\,^2P_{3/2,1/2}) , \tag{1}$$

where $h\nu_0$ represents the required photon energy, corresponding to 8521 Å for excitation to the $6\,^2P_{3/2}$ state and 8944 Å to the $6\,^2P_{1/2}$ state. The second step is the actual ionization, i.e.,

$$\mathrm{Cs}(6\,^2P_{3/2,1/2}) + h\nu \xrightarrow{\sigma_{3/2,1/2}} \mathrm{Cs}^+ + e^- , \tag{2}$$

where $\sigma_{3/2,1/2}$ are the desired cross sections as functions of photon energy $h\nu$. Continuous absorption[12] will take place for photon energies greater than the ionization thresholds, corresponding to wavelengths of 5083 and 4944 Å for the $6\,^2P_{3/2}$ and $6\,^2P_{1/2}$ states, respectively.

In the past photoionization cross sections for cesium have been determined in several ways.[13-16] One of these methods is to determine the absorption of uv light in a column of metal vapor. One of the advantages of this procedure is that the light intensities need not be known absolutely. Disadvantages include: (i) A long path length is required to obtain measurable attenuation; (ii) absolute determination and spatial uniformity of the atom number density is difficult to obtain; (iii) ionization of Cs_2 molecules contributes to the total signal since analysis of the ion products is

not performed.

Another method applicable to both excited and ground-state atoms involves determination of the recombination coefficients in a low-temperature cesium plasma.[3,4] This is illustrated by reaction (2) going from right to left. One of the difficulties in this *indirect* method is to determine the energy distribution of the plasma electrons recombining with the positive ions.

The present experiment represents a first attempt to measure *directly* the photoionization cross section from the $6\,^2P$ fine-structure levels as a function of wavelength. The triple-crossed-beam apparatus used consists of an atomic beam crossed by two photon beams, one for excitation and one for ionization. The three beams intersect within a small volume and produce ions, which are counted. The cross section is then proportional to the count rate.

The material in this paper is organized as follows: In Sec. II we discuss briefly quantum-defect[1] and model-potential[2] calculations which have been useful in obtaining theoretical cross sections. The experimental procedure, including atom excitation and ion production and detection, is described in Sec. III. Finally, a presentation of the results and a discussion of background effects and consistency checks is contained in Sec. IV.

II. THEORY

Several attempts have been made to calculate atomic photoionization cross sections, with various degrees of success.[16] For the most part these calculations have been limited to the photoionization of atoms from the ground state.

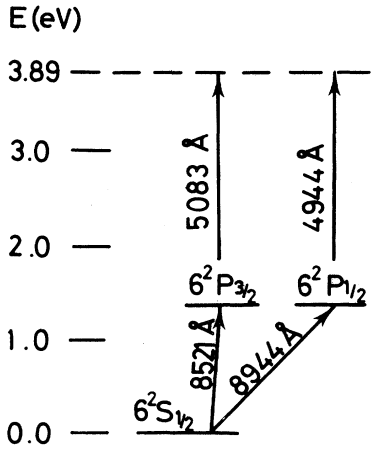

FIG. 1. Partial energy-level diagram for cesium. The "onset" wavelengths for photoionization from the fine-structure states are included.

As early as 1923, Kramers[17] introduced an expression for the photoionization cross section. His work was based on classical electrodynamic theory and the Bohr model of the atom. This formulation met with some success when applied to hydrogen and the lighter hydrogenlike ions. However, when applied to the heavier ions there was considerable discrepancy between theory and available experimental results.

From a quantum-mechanical consideration, the photoionization cross section is proportional to the square of the transition matrix,

$$T_{nl,n'l'} = |\langle nl|\, r\,|n'l'\rangle| \ , \tag{3}$$

where the transition is from a bound state nl to a free state $n'l'$. The problem is then, in principle, to find the proper wave functions and perform the integrations inherent in Eq. (3).

In this paper we shall consider the quantum-defect method (QDM) and the model-potential formulation which give cross sections that can be directly compared with experimental data.

The QDM was first introduced in photoionization by Burgess and Seaton[18] and was later adjusted by Norcross and Stone.[1] Since fine structure was not taken into account, the cross section represent an average over the $6\,^2P_{1/2}$ and $6\,^2P_{3/2}$ states. Similar calculations have been carried out by Moskvin,[19] but without the adjustment.

The cross section for photoionization, $\sigma(\nu)$, is related to the recombination cross section $\sigma_R(v)$ by the relation[20]

$$\sigma(\nu) = \frac{(mv)^2}{2(2l+1)(h\nu/c)^2}\,(1 - e^{-h\nu/kT})\sigma_R(v) \ , \tag{4}$$

where T is the temperature of the equilibrium plasma, and v is the electron velocity resulting in the emission of a photon of energy $h\nu$. [Standard notation has been for the other symbols in Eq. (4).] Since $e^{-h\nu/kT} \ll 1$, the photoionization cross section will be of the form

$$\sigma(\nu) \propto v^2\sigma_R(v)\lambda^2 \ . \tag{5}$$

Analyses of the recombination measurements of Mohler and Boeckner[3] and Agnew and Summers[4] result in wavelength-dependent cross sections which will later be compared with the present results. It should also be mentioned that Klucharev and Dobrolege[21] has recently measured the average cross section with an argon-ion laser at 4880 Å.

All results discussed so far pertain only to the *average* cross section. Fortunately, photoionization from cesium atoms prepared in specific fine-structure states has been studied using different model potentials. The formulations of Weisheit[2]

and of Norcross[22] both include spin-orbit perturbation and core polarization, but the two authors apply different methods of parametrization in the potentials. Model-potential calculations have also been done by Caves and Dalgarno[23] on lithium.

III. EXPERIMENT

A. Over-all view

Since we were interested in total photoionization cross sections the angular and velocity distributions of the photoelectrons were not studied. Furthermore, no attempts were made to include polarization effects[24] relative to target atoms, light sources, and emitted electrons.

A schematic diagram of the apparatus is shown in Fig. 2. The entire system is housed in an evacuated chamber with background pressure of the order of 10^{-9} Torr. The cold surfaces are kept close to liquid-nitrogen temperature to minimize the coating of insulating surfaces with cesium. The atomic beam passes through the region labeled "interaction region," where it is intersected by the two photon beams. Also indicated in the diagram is the surface-ionization detector (SID) consisting of a hot tungsten wire and a collector plate. In the following the major parts of the apparatus are described in more detail.

B. Atomic beam

The atomic beam is produced in a two-stage oven. The first stage is a reservoir made of an oxygen-free high-conductivity (OFHC) copper "pinch-off" tube. A commercially available glass ampule containing 2 g of 99.9% pure cesium is inserted into the pinch-off tube and broken by squeezing after vacuum is attained. (We note that impurities are of little importance in this experiment since they are not excited by the cesium resonance radiation.)

The second stage is the oven proper and consists of a thick-walled stainless steel tube covered at the end by a collimating-hole structure[25] (CHS) of 1-in.^{2} surface area. This part of the oven is heated by a molybdenum wire filament and maintained at a temperature T_2 about 100°C above the reservoir temperature. [The reasons for the excess temperature in the oven are to avoid condensation and clogging in the capillaries and to decrease the dimer (Cs_2) concentration in the beam.] The atomic beam is further collimated by a 1-cm^2 aperture in the first cold surface.

The density of Cs atoms in the interaction region was determined by means of a tungsten surface-ionization detector[26] taking the necessary geometrical corrections into account. The temperature of the hot wire was found from the tables of Jones and Langmuir.[27] The number densities in the experiment ranged from 5×10^{9}–5×10^{10} cm^{-3}.

C. Excitation rates

The success of all experiments concerned with excited target atoms rests upon the density n^* of such atoms. Ideally, in a simple two-level system, one would like to saturate the resonance transition to attain $n^* = \frac{1}{2}n_0$, where n_0 is the initial ground-state density. This would greatly simplify an absolute determination of n^*.

In the case of cesium, light sources for the excitation radiation should provide the two resonance wavelengths, 8521 and 8944 Å, for the photoexcitation of the fine-structure levels. A pulsed GaAs laser[28,29] was initially considered for this source, and even though the number of photons per pulse was adequate, it was deemed unsatisfactory because of problems encountered with stability and frequency tuning.

The light source finally chosen was a commercial dc cesium discharge lamp,[30] which produced sufficient photon flux in the two resonance lines. The desired line was selected with the aid of an interference filter. (We realize that the experiment would have been easier to perform if a near-infrared dye laser had been available. Lacking such facilities during the course of this investigation, the "classical" procedure discussed above had to be used.)

If the atoms in the beam are irradiated with photons of frequency ν, the rate of excited atoms produced at a position x is

$$\frac{dn_\nu^*(x)}{dt} = -\frac{n_\nu^*(x)}{\tau} + j_\nu(x)k'_\nu \,, \tag{6}$$

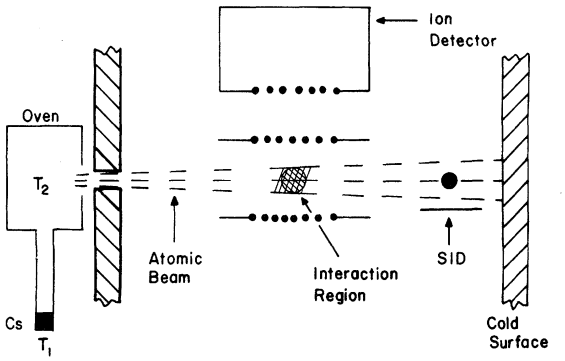

FIG. 2. Schematic drawing of photoionization apparatus. The interaction region is exposed to light beams for excitation and ionization. The ions produced are extracted through a system of parallel grids and detected with a Johnston multiplier. SID is a surface ionization detector for measuring the flux of cesium atoms.

where $j_\nu(x)$ represents the photon flux per frequency interval, k'_ν is the absorption coefficient, and τ is the lifetime of the excited atoms.

The steady-state solution, which applies to our experimental situation, yields the density of excited atoms averaged over an absorption length l,

$$\langle n_\nu \rangle = \frac{\tau j_\nu(0)}{l} (1 - e^{-k'_\nu l}) , \quad (7)$$

where $j_\nu(0)$ is the incident light flux.

The total number of excited atoms was found by integrating over all frequencies using the procedure discussed by Mitchell and Zemansky.[31] The more detailed treatment developed by Bell *et al.*[32] was not deemed necessary in the present application. For practical reasons in the experiment the angle between the atom beam and the exciting light beam was 60°, thus taking advantage of the large velocity spread to produce a wide absorption line. With a total excitation photon flux of 10^{15} cm^{-2} sec^{-1} we estimate n^* to be in the range from 5×10^4 to 5×10^5 cm^{-3} from Eq. (7). The ionization rate expected on the basis of these numbers is discussed in Sec. III D.

D. Ion production and detection

The number of ions which is produced at a wavelength λ per wavelength interval per sec within the interaction volume V due to photoionization of excited atoms can be written as

$$N^+(\lambda) = n^* \sigma(\lambda) j'_2(\lambda) V , \quad (8)$$

where $\sigma(\lambda)$ is the photoionization cross section from the excited state and $j'_2(\lambda)$ represents the photon flux per wavelength interval from the ionization light source. The total number of ions produced per sec can be found by integrating the above equation over the full bandwidth of the ionization light source, $2\Delta\lambda$. If we assume $\sigma(\lambda)$ to be constant over the bandwidth and with a value $\sigma(\lambda_2)$, which is a good approximation since $\sigma(\lambda)$ is slowly varying,[1-4] then the ion-production rate is

$$N^+(\lambda_2) = n^* V \sigma(\lambda_2) \int_{\lambda_2 - \Delta\lambda}^{\lambda_2 + \Delta\lambda} j'_2(\lambda)\, d\lambda , \quad (9)$$

where the integral in Eq. (9) represents the total ionizing photon flux. This correction was only of importance around 5000 Å, where part of the ionizing light flux was not sufficiently energetic to cause ionization.

An order-of-magnitude estimate for $N^+(\lambda_2)$ can now be made. With an interaction volume of 0.1 cm^3, a cross section of 6×10^{-18} cm^2, and a photon flux of 5×10^{14} cm^{-2} sec^{-1}, which are approximate values at $\lambda = 4360$ Å, the estimated value of $N^+(\lambda_2)$ is 50 ions/sec, and the observed count rate is 5 ions/sec.

A high-pressure mercury-xenon lamp[33] was chosen for the ionization light source. It contains several intense spectral lines between 5500 and 2500 Å, superimposed on a strong continuum. The main disadvantage of this lamp was the absence of strong lines near threshold, around 5000 Å.

A $\frac{1}{4}$-m high-intensity monochromator was used to isolate the strong lines of the Hg-Xe lamp. A compromise between resolution and high photon flux resulted in a full-width half-maximum line profile of 150 Å. Calibrated photodiodes[34] were used to measure the ionizing light intensity.

Ions are produced in a region between two parallel grids and accelerated towards a particle detector (see Fig. 2). Grids were used to minimize surface effects. The wire mesh is approximately 80% transmitting and has an area much larger than the interaction region, thereby assuring a high collection efficiency for ions. Ions passing the entrance grid to the detection region are accelerated towards a 20-stage focused-mesh Cu-Be electron multiplier with a 1-in.^{2} active counting area.[35]

Most background effects in the experiment are discriminated against by mechanical chopping of the excitation radiation. Practically, the count rates were analyzed by a Digital Synchronous Computer (DSC).[36] The reference signal used to gate the DSC is derived from a photodiode modulated by the excitation-radiation mechanical chopper. The preset counting time for each channel was 45 msec and the modulation frequency was 10 Hz. Under proper operating conditions the difference of the counts stored in the two channels is proportional to the number of two-step photoionization events that occurred during the counting time. Thus the effects of slow drifts in background counts are minimized and long data acquisition times are possible. These techniques have allowed reliable signal detection for signal-to-noise ratios as small as 1:10.[3]

IV. RESULTS AND DISCUSSION

A. Statistical considerations

As a result of the large total count rate, typically of the order of 500 sec^{-1}, and small net count rate, typically from 0.1 to 5 sec^{-1}, it is necessary to consider the statistical variations involved in acquiring data.[37] The standard deviation in the *net* count rate is given by

$$\sigma = \left(\frac{\langle x \rangle + \langle y \rangle}{n} \right)^{1/2} , \quad (10)$$

where $\langle x \rangle$ and $\langle y \rangle$ represent the "signal plus

noise" and "noise" channels, averaged over a total of n observations. Typically in this experiment, a total counting time of 3–10 h was required to stay within an error of 20%.

B. Background effects and consistency checks

Along with the two-step ionization process there are additional processes which can produce ions and background counts in the apparatus. The total background count rate is due to a composite of volume and surface interactions, as discussed in items 1–5 and 6 and 7 below:

1. $Cs(6\,^2S_{1/2}) + h\nu \rightarrow Cs^+ + e^-$

Photoionization of ground-state cesium atoms occurs only for wavelengths of the ionizing light below 3184 Å. At this threshold we estimate a count rate of 10^2 sec^{-1} using a photon flux of 10^{12} cm^{-2} sec^{-1} and a cross section of 10^{-19} cm^2. The process thus adds considerably to the total count rate below the one-photon ionization threshold but is effectively discriminated against by the modulation scheme used in the experiment.

2. $Cs(6\,^2P) + Cs(6\,^2P) \rightarrow Cs_2^+ + e^-$

The cross section for associative ionization has been studied[38–40] and found to be of the order of 10^{-18} cm^2. The process can be studied separately by turning the ionizing light off while modulating the excitation light. No net ion count rate was observed under these conditions. The estimated count rate is below 10^{-3} sec^{-1}.

3. $Cs_2 + h\nu \begin{cases} \rightarrow Cs_2^+ + e^- \\ \rightarrow Cs^+ + Cs + e^- \end{cases}$

The cross section for photoionization of the cesium dimer is of the same order of magnitude as the cross section for Cs*.[41] The concentration of cesium dimers is minimized by keeping the temperature of the oven 100°C above that of the cesium reservoir. An estimated count rate of 1 sec^{-1} is discriminated against by the chopping technique since this process is independent of the intensity of the exciting light.

4. $Cs + e^- \rightarrow Cs^+ + 2e^-$

In the present apparatus large numbers of secondary electrons are liberated from cesiated surfaces by the incident radiation. We minimize available surface areas by using grids instead of plates. These photoelectrons can be accelerated through the atomic-beam region giving rise to electron-impact ionization.[42–46] Since the cross section for electron-impact ionization of ground-state cesium atoms is zero below the ionization threshold of 3.89 eV, we eliminate this contribution by applying a sufficiently weak electric field in the interaction region. If high-energy electrons are present and collide with beam atoms the resulting ion count is discriminated against by the modulation technique. We report that no photoelectrons were generated by the excitation light at wavelengths of 8944 and 8521 Å.

5. $Cs(6\,^2P) + e^- \rightarrow Cs^+ + 2e^-$

Since the rate of ions produced in electron collisions with *excited* atoms does depend on the intensity of the excitation light, the modulation scheme is unable to eliminate this particular background effect. With $n^* \approx 10^6$ cm^{-3}, a measured flux of stray electrons of 10^5 cm^{-2} sec^{-1}, and a maximum cross section[46] of 3×10^{-15} cm^2, we estimate a count rate of 3×10^{-5} cm^{-3} sec^{-1}. However, by maintaining the electric field in the interaction region sufficiently low, the energy of the stray electrons produced at the grid directly above and closest to the atomic beam can be controlled to be below the ionization threshold of about 2.4 eV for the excited atoms. The contribution from electron impact is thus orders of magnitudes less than the expected count rate due to photoionization of excited atoms.

6. *Thermionic emission*

Thermionically emitted electrons from the atomic-oven part of the apparatus are prevented from reaching the interaction region by keeping the latter at a negative potential with respect to the oven. Eventual positive ions produced in the oven were deflected by a transverse electric field immediately after the oven exit (not shown in Fig. 2). In practice we found that no ions were present in the atomic beam.

7. *Photoionic emission*

Positive ions may be emitted from a cesiated surface exposed to light, even at room temperature. Medicus and Breaux[47] have presented evidence in support of this process, but their analysis has been criticized by Shaw and Stickney.[48] In the present apparatus, the ionization light is collimated as much as practical; in spite of this precaution a small amount of stray light will strike the ion-extraction grids. We observed that before the cesium ampule was broken there was less than 1 background count per second with the light sources in place. After the ampule was broken and cesium allowed to deposit on the electrodes, but turning the atomic beam off, the background count rate increased to approximately 500 sec^{-1}. Although this experiment is not designed to study the photoionic effect, we have evidence that the

observed background count rate is due in part to this process.

In reviewing the above list of background effects we find that most of them are eliminated thanks to the chopping of the excitation light. Items 2 and 5 do depend on the intensity of the excitation light, but their contributions are orders of magnitude below the count rate due to photoionization of excited cesium atoms, and can therefore be ignored on numerical grounds.

The observed ion count rates are expected to be proportional to the density of ground-state cesium atoms and to the intensities of the exciting and ionizing light beams. Consistency checks were carried out and demonstrated linearity (within the experimental error bars) as the density was changed by a factor of 2 and the two light intensities by a factor of 5.

C. Experimental data and discussion

Relative measurements of the photoionization cross sections for the $6^2P_{3/2}$ and $6^2P_{1/2}$ states were taken at wavelengths corresponding to the intense spectral lines of the Hg-Xe ionization source, 5460, 4358, 4047, 3663, 3130, and 2537 Å. The signal-to-noise ratio attainable for each of the above lines was approximately 1:100. Additional measurements were made in the continuum of the Hg-Xe lamp and resulted in signal-to-noise ratios from 1:500 and 1:2000 for the $6^3P_{3/2}$ and $6^2P_{1/2}$ states, respectively. The smaller signal-to-noise ratio for the $6^2P_{1/2}$ measurements is due to the lower intensity of the 8944-Å excitation radiation and the lower absorption oscillator strength. This effect was not as noticeable for wavelengths $\leq$4358 Å because of the high intensity of the ionization light source.

The results normalized to Weisheit's $\sigma_{3/2}$ cross section at 4360 Å are shown in Table I.

TABLE I. Cross sections for photoionization of the $6^2P_{1/2}$ and $6^2P_{3/2}$ states in cesium.

λ (Å)	$\sigma_{1/2}$ (10^{-18} cm^2)	$\sigma_{3/2}$ (10^{-18} cm^2)
5460	0 ± 0.2	0 ± 0.2
5300	0 ± 0.3	0 ± 1.8
5100	0 ± 3.2	...
5000	0 ± 3.2	21.5 ± 2.2
4900	23.7 ± 4.7	...
4700	20.5 ± 6.4	19.6 ± 3.0
4360	17.5 ± 1.6	16.5 ± 1.2
4050	14.0 ± 1.4	14.0 ± 1.4
3670	11.4 ± 1.7	8.2 ± 1.0
3125	5.6 ± 1.4	3.4 ± 0.8
2500	0 ± 1.4	1.9 ± 1.1

A very important consistency test is to check that the cross sections are zero for wavelengths above the respective ionization threshold. These measurements are also included in Figs. 3 and 4. Improper alignment of the light beams and inaccurate triggering of the counters could easily cause nonzero difference count rates. All experimental points have been corrected for the spread in wavelength of the ionizing light as discussed in Eq. (9).

We notice that in the overlapping wavelength region the difference between $\sigma_{1/2}$ and $\sigma_{3/2}$ is equal to zero within the experimental uncertainty. Experimentally, before the normalization was carried out, the relative cross sections for the $6^2P_{3/2,1/2}$ states were the same when taking the different oscillator strengths and exciting-light intensities into account. Since the spin-orbit perturbation of the bound and continuum orbitals is not large, it is also found theoretically[2] that $\sigma_{1/2} \approx \sigma_{3/2}$. The cross sections are plotted on linear scales in Figs. 3 and 4 and compared with the model-potential calculations of Weisheit[2] and of Norcross.[22] The two theories agree very closely in the higher-wavelength region, but differ considerably at 2000 Å. Weisheit used a total of seven adjustable parameters in his calculation, whereas Norcross used only two. The effect of core polarization becomes increasingly important at shorter wavelengths and was calculated differently by the two theoretical

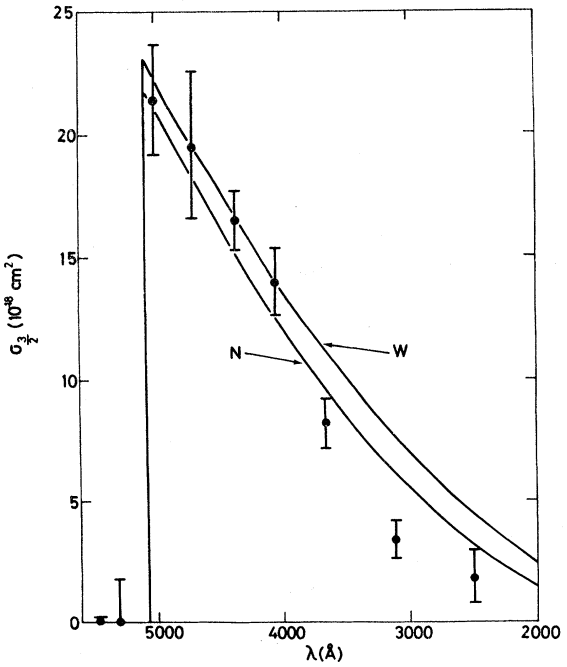

FIG. 3. $\sigma_{3/2}$ in units of 10^{-18} cm^2 as a function of wavelength. N: Norcross, Ref. 22; W: Weisheit, Ref. 2.

authors. The experimental points for both cross sections are partly below the calculated values for wavelengths below 4000 Å. This effect was found for various optical geometries using interference filters or the monochromator discussed previously. Since the diameter of the ion detector is larger than the length of the interaction region, we found that the detection probability was independent of the position of generation of the photoions.

It is of interest to compare the shape of our $\sigma_{1/2}$ and $\sigma_{3/2}$ cross sections with the results of previous recombination cross sections. The combined, or mean, cross section that is derived from recombination measurements can be written as

$$\sigma_M = \tfrac{1}{3}\sigma_{1/2} + \tfrac{2}{3}\sigma_{3/2} . \qquad (11)$$

If the energy of the photons is only sufficiently high to ionize the $6\,^2P_{3/2}$ state, we have $\sigma_M = \sigma_{3/2}$ for $5083 \geq \lambda_2 \geq 4944$ Å. Weisheit found from his calculation that the recombination cross section $\sigma_R(v)$ multiplied by the electron velocity squared was very nearly constant in the wavelength region relevant to this discussion. This implies, from Eq. (5), that $\sigma_M \propto \lambda^2$, which is graphically illustrated in Fig. 5. The same wavelength dependence was found by Agnew and Summers,[4] who performed recombination measurements between 5000 and 4000 Å. On the other hand, the measurements of Mohler and Boeckner[3] indicate a λ^4 dependence

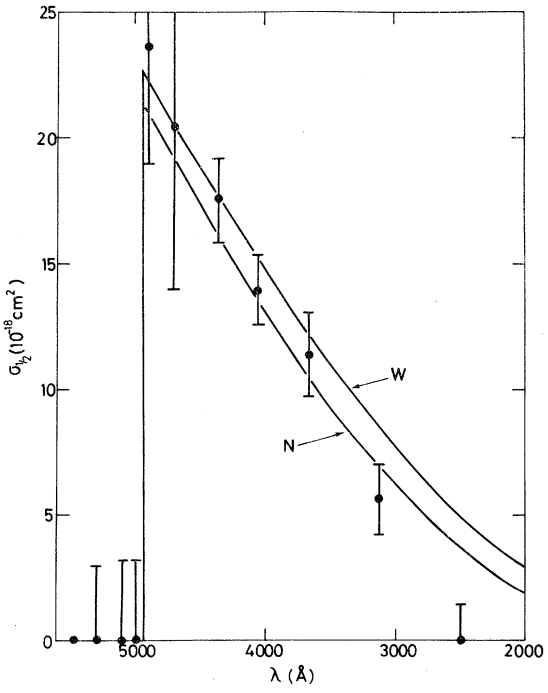

FIG. 4. $\sigma_{1/2}$ in units of 10^{-18} cm^2. Same legend as in Fig. 3.

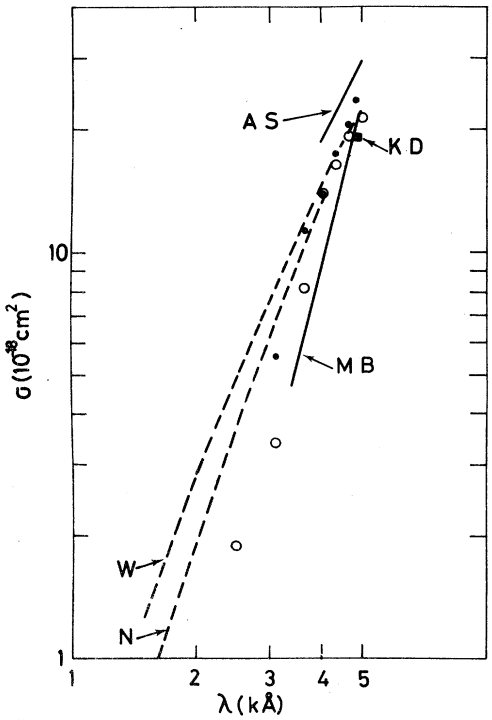

FIG. 5. Wavelength behavior of $\sigma_{1/2}$ (●), $\sigma_{3/2}$ (○), and σ_M. AS: Agnew and Summers, Ref. 4; MB: Mohler and Boeckner, Ref. 3; W: Weisheit, Ref. 2; N: Norcross, Ref. 22. The single point at 4880 Å (KD) is due to Klucharev and Dobrolege, Ref. 21. The present $\sigma_{1/2}$ and $\sigma_{3/2}$ measurements coincide at 4050 Å.

from 3400–5000 Å. In order to obtain absolute cross sections from recombination measurements the intensity of the continuum light must be determined absolutely. The electron density velocity distribution must also be known. The disagreement between various recombination experiments is therefore not surprising.

The present results for $\sigma_{1/2}$ and $\sigma_{3/2}$ when plotted on the double logarithmic scale in Fig. 5 indicate a λ^2 dependence from 4000 to 5000 Å, but appear to fall off with an exponent of 3–4 at the shorter wavelengths. For comparison it should be mentioned that the hydrogenic cross section behaves as λ^3 at threshold. However, the $6\,^2P$ states of cesium are far from hydrogenic. It would be of interest to study the wavelength dependence for photoionization of higher excited states in cesium and other alkali-metal elements.

ACKNOWLEDGMENTS

The authors are indebted to D. W. Norcross for making available his unpublished model-potential calculations. We would also like to thank M. J. Van der Wiel for constructive comments on the manuscript.

*Supported in part by Office of Naval Research.

†Permanent address.

‡Present address: Natl. Bur. Stand., Washington, D. C. 20234.

§Present address: Teledyne Brown Engineering, Huntsville, Ala. 35805.

[1]D. W. Norcross and P. M. Stone, J. Quant. Spectrosc. Radiat. Transfer 6, 277 (1966).

[2]J. C. Weisheit, J. Quant. Spectrosc. Radiat. Transfer 12, 1241 (1972).

[3]F. L. Mohler and C. Boeckner, J. Res. Natl. Bur. Stand. (U. S.) 2, 489 (1929); F. L. Mohler, J. Res. Natl. Bur. Stand. (U. S.) 10, 771 (1933). The first of these papers gives the wavelength dependence of the recombination cross section into the $6\,^2P$ states while the second reports an absolute recombination cross section of 1.7 $\times 10^{-21}$ cm^2 at 4400 Å.

[4]L. Agnew and C. Summers, Proceedings of the Seventh International Conference on Phenomena in Ionized Gases, Belgrade, 1965, p. 574 (unpublished).

[5]E. W. McDaniel and M. R. C. McDowell, *Case Studies in Atomic Collision Physics* (Wiley, New York, 1969), Vol. 1, pp. 49–71.

[6]S. A. Tuccio, J. W. Dubrin, O. G. Peterson, and B. B. Snavely, Lawrence Livermore Radiation Laboratory Report No. UCRL-75696, 1974 (unpublished).

[7]B. Bederson, Comments Mol. Phys. 4, 103 (1973).

[8]M. J. Van der Wiel, E. H. A. Granneman, M. Klewer, and K. J. Nygaard, FOM–Institute for Atomic and Molecular Physics, Amsterdam, The Netherlands.

[9]R. F. Stebbings, F. B. Dunning, F. K. Tittel, and R. D. Rundel, Phys. Rev. Lett. 30, 815 (1973). See also invited paper by R. F. Stebbings, F. B. Dunning, and R. D. Rundel, in *Atomic Physics 4, Proceedings of the Fourth International Conference on Atomic Physics, Heidelberg, 1974*, edited by E. W. Weber and A. Winnacker (Plenum, New York, 1975), pp. 713–730.

[10]A. C. Gallagher and G. York, Rev. Sci. Instrum. 45, 662 (1974).

[11]D. J. Bradley, P. Ewart, J. V. Nicholas, and J. R. D. Shaw, J. Phys. B 6, 1594 (1973); Phys. Rev. Lett. 31, 263 (1973).

[12]Excitation to autoionizing levels from the $6\,^2P$ states requires a photon energy in excess of 9.9 eV and is therefore excluded due to the limited spectral range used in this investigation. Autoionization is discussed in more detail by Y. B. Hahn and K. J. Nygaard, Phys. Rev. A 4, 125 (1971).

[13]R. D. Hudson and L. J. Kieffer, At. Data 2, 205 (1971).

[14]R. D. Hudson, Rev. Geophys. Space Phys. 9, 305 (1971).

[15]H. J. J. Braddick and R. W. Ditchburn, Proc. R. Soc. Lond. 143, 472 (1934).

[16]G. V. Marr, *Photoionization Processes in Gases* (Academic, New York, 1967), pp. 31–54.

[17]H. A. Kramers, Philos. Mag. 46, 836 (1923).

[18]A. Burgess and M. J. Seaton, Mon. Not. R. Astron. Soc. 120, 121 (1959).

[19]Yu. V. Moskvin, Opt. Spectrosc. 15, 316 (1963).

[20]E. A. Milne, Philos. Mag. 47, 209 (1924).

[21]A. N. Klucharev and B. V. D. Dobrolege, in *Abstracts of Papers, Eighth International Conference on the Physics of Electronic and Atomic Collisions, Belgrade, 1973*, edited by B. C. Cobić and M. V. Kurepa (Institute of Physics, Belgrade, Yugoslavia), pp. 553 and 554.

[22]Photoionization of Cs($6\,^2S_{1/2}$) is discussed by D. W. Norcross, Phys. Rev. A 7, 606 (1973). He has applied the same method to the $6\,^2P_{3/2,1/2}$ states, and provided us with the results in a private communication.

[23]T. C. Caves and A. Dalgarno, J. Quant. Spectrosc. Radiat. Transfer 12, 1539 (1972).

[24]G. Baum, M. S. Lubell, and W. Raith, Phys. Rev. Lett. 25, 267 (1970); K. Kessler and J. Lorenz, Phys. Rev. Lett. 24, 87 (1970).

[25]The CHS was supplied by the Brunswick Corp., Skokie, Ill. 60076, and contained 5500 holes per in.^{2}, each with a diameter-to-length ratio of 1:20.

[26]M. Kaminsky, *Atomic and Ionic Impact Phenomena on Metal Surfaces* (Springer, Berlin, 1965), pp. 98–124.

[27]H. A. Jones and I. Langmuir, Gen. Electr. Rev. 30, 310 (1927).

[28]R. E. Hebner, Jr. and K. J. Nygaard, Physica 58, 225 (1972).

[29]R. E. Hebner, Jr. and K. J. Nygaard, J. Opt. Soc. Am. 61, 1455 (1971).

[30]Cesium Osram Spectral Lamp from the Edmund Scientific Co.

[31]A. C. G. Mitchell and M. W. Zemansky, *Radiation and Excited Atoms* (MacMillan, New York, 1934), pp. 92–151.

[32]G. D. Bell, M. H. Davis, R. B. King, and M. P. Routly, Astrophys. J. 127, 775 (1958).

[33]250-W high-pressure Hg-Xe vapor lamp and housing from Ushio Electronics, Tokyo, Japan.

[34]Calibrated photodiodes from United Detector Technology, Inc., Santa Monica, Calif.

[35]Johnston Laboratories, Inc., Cockeysville, Md.

[36]Model 1110 Digital Synchronous Computer from SSR Instruments Co., Santa Monica, Calif.

[37]W. J. Price, *Nuclear Radiation Detection*, 2nd ed. (McGraw-Hill, New York, 1964), pp. 52–69.

[38]K. Freudenberg, Z. Phys. 67, 417 (1931).

[39]D. H. Pollock and A. O. Jensen, J. Appl. Phys. 36, 3184 (1965).

[40]A. G. F. Kniazzeh, *Report on the Twenty-Sixth Annual Conference on Physical Electronics* (MIT, Cambridge, Mass., 1966), p. 1.

[41]D. N. Creek and C. V. Marr, Proc. R. Soc. A 304, 233 (1968); D. Popescu, M. L. Pascu, C. B. Collins, B. W. Johnson, and Iovitzu Popescue, Phys. Rev. A 8, 1666 (1973).

[42]R. H. McFarland and J. D. Kinney, Phys. Rev. A 137, 1058 (1965).

[43]H. Heil and B. Scott, Phys. Rev. A 145, 279 (1966).

[44]Yu. P. Korchevoi and A. M. Przonski, Zh. Eksp. Teor. Fiz. 51, 1617 (1966) [Sov. Phys.—JETP 24, 1089 (1967)].

[45]K. J. Nygaard, J. Chem. Phys. 49, 1995 (1968).

[46]M. Gryzinski, in *Atomic Collision Processes*, edited by M. R. C. McDowell (North-Holland, Amsterdam, 1964), pp. 226–236.

[47]O. P. Breaux and G. Medicus, Phys. Rev. Lett. 16, 392 (1966).

[48]M. L. Shaw and R. E. Stickney, Phys. Rev. Lett. 18, 824 (1967).