Measurement of the photoionization cross section of the $6P_{3/2}$ state of cesium

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We report the measurement of the absolute photoionization cross section for the $6P_{3/2}$ state of cesium. Cross sections were determined by measuring the photoionization rate of cesium atoms confined in a magneto-optical trap. The photoionization rate was measured by monitoring the decay of trap fluorescence during exposure to ionizing laser radiation. The measurements were made in the wavelength range 457.9 to 501.7 nm using several lines from an Ar-ion laser. Our results are compared to other experimental measurements as well as to existing theories. [S1050-2947(99)06603-2]

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The photoionization of cold, trapped atoms was first used by Dinneen *et al.* to measure the photoionization cross section of the $5P_{3/2}$ state in rubidium [1]. In their measurements, rubidium atoms were loaded into a magneto-optical trap (MOT) from an atomic beam. The trapping beams created an excited-state population by continually exciting the trapped atoms. The MOT was exposed to ionizing radiation after interrupting the atomic beam. The ionized Rb atoms escaped the trap and produced a decrease in the trap fluorescence. The detection of the fluorescence decay provided a direct measurement of the photoionization rate and allowed the cross section to be determined. More recently, a similar technique was used in vapor-filled MOTs to measure photoionization cross sections for rubidium [2] and cesium [3]. In these measurements the photoionization rate was determined from the change in the MOT loading rate and additionally, for cesium, from the change in the equilibrium number of trapped atoms when the MOT was subjected to photoionizing laser light.

The present cross section measurements for the $6P_{3/2}$ state of cesium were made in a vapor-loaded MOT using a variation of the techniques described above. After loading the trap to a steady-state population, the photoionization rates were determined by measuring the loss rate of atoms from the trap. The loss rate contribution due to background collisions was removed using subsequent measurements of the MOT loading rate after the ionizing light was turned off. The measurements were carried out for several wavelengths close to the photoionization threshold of 508.1 nm. Our results are in agreement with previous experimental and theoretical results, including the recent measurements by Maragò *et al.* [3].

A standard magneto-optical trap (MOT), loaded from the background vapor, was used to cool and trap neutral Cs atoms. The trapping laser was an injection-locked, temperature-stabilized diode laser that provided a maximum total MOT intensity of 130 $\mathrm{mW/cm^2}$ in the six MOT beams. The diameter of the trapping beams was 0.8 cm. The trapping laser was injected with 10 mW of light from a master diode laser that was frequency-locked one natural linewidth ($\delta=-\Gamma$) below the $F=4$ to $F'=5$ trapping transition ($\lambda=852$ nm). A third diode laser provided about 1 mW for the $F=3$ to $F'=4$ repumping transition ($\lambda=894$ nm). The background gas pressure was 10^{-9} Torr, resulting in a trap lifetime of about 5 s. The axial magnetic field gradient was maintained at 11 G/cm throughout the experiment.

The cold cesium atoms were photoionized using several lines from an Argon-ion laser. The Ar^+ beam had an approximately circular Gaussian profile, as measured with a beam profiler, and was expanded to a collimated diameter of 1.0 cm. Because the beam size was much greater than the MOT diameter (<1.0 mm), the ionizing intensity seen by the trapped atoms was relatively uniform and corresponded to the peak of the intensity profile. The ionizing intensities were measured at each Ar^+ wavelength (λ_P) using a silicon detector and a 2.0-mm-diam aperture. We used low ionizing intensities (<0.5 $\mathrm{W/cm^2}$) for all measurements to avoid saturating the photoionization response. The Ar^+ beam was carefully centered on the MOT prior to the measurements by minimizing the detected MOT fluorescence.

The photoionization rates were determined by detecting the decay in trap fluorescence after the Ar^+ laser was shuttered on. The trap fluorescence was focused into a photomultiplier tube (PMT) and recorded as a function of time using a digital oscilloscope. In addition, the loading as a function of time, after turning off the Ar^+ laser, was recorded. Measurements were made at $\lambda_P=496.5$ nm for a range of trapping intensities between 5 and 130 $\mathrm{mW/cm^2}$. Additional measurements were carried out for other Ar^+ wavelengths at a constant trapping intensity of 103 $\mathrm{mW/cm^2}$.

The number of trapped atoms in a MOT is governed by a balance between the atom capture rate (Γ_c), the collisional loss rate (R_L) of atoms from the trap, and, in the presence of ionizing radiation, by the photoionization rate (R_P). The time rate of change of the number (N) of trapped atoms is given by the rate equation

$$\frac{dN}{dt}=\Gamma_c-(R_L+R_P)N. \tag{1}$$

The capture rate depends on the density of hot atoms in the vicinity of the MOT and on the trapping volume, which is determined by the size of the trapping beams. For the relatively high background gas densities considered here, the loss rate is dominated by collisions between the trapped atoms and background gas molecules. In the absence of ionizing radiation, the equilibrium number of trapped atoms is $N_0=\Gamma_c/R_L$.

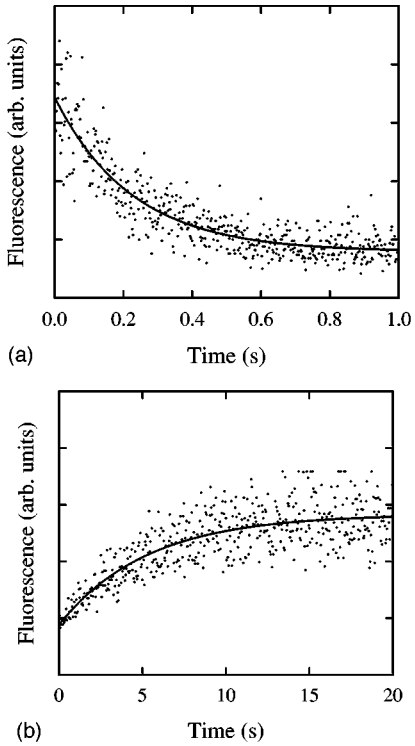

FIG. 1. Typical fluorescence data as a function of time acquired at an ionization wavelength $\lambda_P = 496.5$ nm (a) after the photoionization beam was turned on, and (b) during loading, after the ionization beam was shuttered off. The solid curves are fits to Eqs. (2) and (3) that yielded $R_L + R_P = 4.44(24)\ \mathrm{s}^{-1}$ and $R_L = 0.19(2)\ \mathrm{s}^{-1}$.

When ionizing light is introduced to the MOT, the trapped atom population decreases in time according to

$$N(t) = N_0' + (N_0 - N_0')e^{-(R_L + R_P)t} \tag{2}$$

and attains a new equilibrium population $N_0' = \Gamma_c'(R_L + R_P)^{-1}$. The modified capture rate Γ_c' results from the presence of ionizing radiation in the capture volume. Figure 1(a) shows a representative fluorescence decay as a function of time after turning on the light at $\lambda_P = 496.5$ nm. The total loss rate $R = R_L + R_P$ is found by fitting the data to Eq. (2).

After the total loss rate is determined, a separate measurement of the collisional loss rate is required to determine the contribution due to photoionization. We measure the fluorescence during MOT loading after the Ar^+ beam is shuttered off, as the population increases according to

$$N(t) = N_0 - (N_0 - N_0')e^{-R_L t}. \tag{3}$$

A typical MOT loading curve is shown in Fig. 1(b). Because the background Cs density is not controlled in our experiment, R_L can slowly drift over the course of several measurements. Each photoionization measurement, therefore, is followed by a measurement of the collisional loss rate acquired as the MOT reloads. The photoionization rate R_P is the difference in the decay and loading rates determined by fitting the two curves to Eqs. (2) and (3). Although our measured collisional loss rates R_L are small (typically about $0.2\ \mathrm{s}^{-1}$), they contribute significantly to the overall loss rate R when the photoionization rate is also small, such as at low trapping intensities or low ionization intensities.

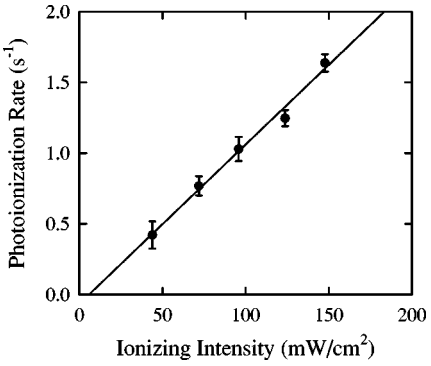

FIG. 2. Photoionization rates measured for several ionizing intensities. The data were acquired at an ionization wavelength $\lambda_P = 488.0$ nm and a total trapping intensity $I_t = 20\ \mathrm{mW/cm}^2$. The solid line is a linear fit to the data.

The photoionization rate is related to the intensity I_P of the ionizing light through the expression

$$R_P = \left(\frac{I_P}{h\nu}\right)\sigma f, \tag{4}$$

where $I_P/h\nu$ is the ionizing photon flux, σ is the cross section for photoionization from the excited $(6P_{3/2})$ state of cesium, and f is the fraction of trapped atoms in the excited state. The linear intensity dependence of Eq. (4) is valid for low intensities that do not saturate the photoionization. A linear dependence was verified by measuring the photoionization rate for a range of ionization intensities, and the results are shown in Fig. 2. The linear fit to the data goes to zero for zero intensity within the uncertainty of the data, indicating that the loss rate $R_P = R - R_L$ corresponds solely to photoionization.

If the excited state fraction is known, Eq. (4) can be used to determine the cross section. Following Dinneen *et al.* [1] we used the expression for a two-state atom,

$$f = \frac{(I_t/I_{sat}^{\delta})}{2(I_t/I_{sat}^{\delta}) + 1}, \tag{5}$$

where I_t is the total trapping intensity. The parameter I_{sat}^{δ} is related to the on-resonance saturation intensity $I_{sat}^{(0)}$ and the frequency detuning (δ) of the trapping laser by

$$I_{sat}^{\delta} = I_{sat}^{(0)}[(2\delta/\Gamma)^2 + 1]. \tag{6}$$

The photoionization cross section is thus determined by measuring the ionization rate for a range of trapping intensities and fitting the data using Eqs. (4) and (5) with I_{sat}^{δ} and σ as free parameters.

The photoionization rates measured at $\lambda_P = 496.5$ nm are shown in Fig. 3 as a function of the total trapping intensity. The fit results were $\sigma = 1.86(15) \times 10^{-17}\ \mathrm{cm}^2$ and $I_{sat}^{\delta} = 27(6)\ \mathrm{mW/cm}^2$. Using a detuning $\delta = -\Gamma$ gives an on-resonance saturation intensity of $5.4(1.2)\ \mathrm{mW/cm}^2$, in reasonable agreement with the value $6.75\ \mathrm{mW/cm}^2$ expected for equally populated m_F levels.

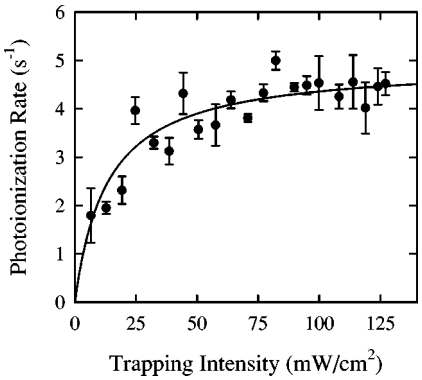

FIG. 3. Saturation of the photoionization rate with trapping laser intensity for $\lambda_P = 496.5$ nm. The solid curve is a fit to the experimental data using Eqs. (4) and (5).

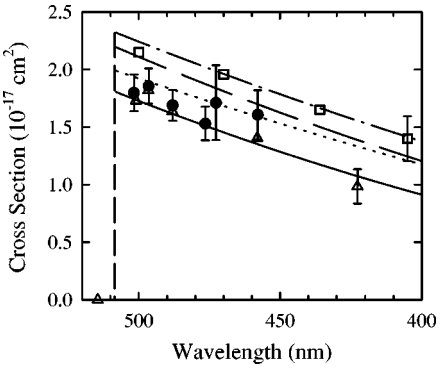

FIG. 4. Photoionization cross sections plotted as a function of wavelength. The closed circles represent our experimental data, and the open triangles and open squares represent cross-section measurements by Moragò *et al.* [3] and Nygaard *et al.* [4], respectively. The error bars for the data from Refs. [3] and [4] were omitted for clarity, but typical error bars are shown for the shortest wavelength points. The dotted-dashed, dashed, dotted, and solid curves are the theoretical results of Weisheit [5], Norcross [6], Msezane [7], and Lahiri and Manson [8].

Additional measurements were carried out at a constant trapping intensity of 103 mW/cm^2 for five additional ionization wavelengths (Fig. 4). The cross sections at these wavelengths were calculated using Eq. (4) and the excited state fraction $f = 0.44(1)$ determined from the $\lambda_P = 496.5$ nm curve (Fig. 3). Also shown in Fig. 4 are previous experimental results by Nygaard *et al.* [4] and Moragò *et al.* [3]. In Ref. [3], the cross sections were determined from the measured photoionization rate as well as from the equilibrium number of trapped atoms during photoionization. The triangles in Fig. 4 represent the average of those two results, which were generally consistent with each other to within 15%. Our results are consistent with the averaged results of Ref. [3], and are within the uncertainty of the results of Ref. [4].

The results of four theoretical calculations are also shown in Fig. 4. These include two model potential calculations [5,6], a Hartree-Fock calculation [7], and a Hartree-Slater calculation [8]. The Hartree-Fock curve that is shown for Ref. [7] is an average of the calculated length and velocity cross sections. Our results are consistent with both of the *ab initio* calculations, but generally fall below the results of the semiempirical calculations. The apparent better agreement of the data of Nygaard *et al.* to the semiempirical results is artificial, as those relative measurements were normalized to the calculations of Ref. [5].

In conclusion, we have measured the photoionization cross section for the $6P_{3/2}$ state of cesium for six wavelengths close to the ionization threshold. Our technique is a variation of recent measurements in which the photoionization rates are determined by measuring the atomic loss rates in a MOT during exposure to ionizing light. Our technique is flexible and can be used for any species that can be confined in a vapor MOT. In addition, it can be used in systems with relatively high background pressures because it corrects for the effects of collisional losses. Our results for cesium are in good agreement with published experimental and theoretical data.

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