Polarizabilities of cesium $(10-13)D_{3/2,5/2}$ states

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The scalar and tensor polarizabilities of the cesium $(10-13)D_{3/2,5/2}$ states were found with uncertainties of less than 0.3%. This experiment measured the voltage required for atoms excited by a laser beam in an electric field to be simultaneously in resonance as atoms excited by a frequency sideband of the laser in a field-free region. The results are in reasonable agreement with theoretical calculations. [S1050-2947(97)07612-9]

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Atomic polarizabilities are important for determining such quantities as charge-exchange cross sections, van der Waals constants, and dielectric constants [1,2] as well as measuring electric fields in plasmas [3]. Several recent experiments have obtained polarizabilities by precisely measuring Stark shifts as is reviewed in Ref. [4]. The accuracy of these data is significantly better than is obtained by the best measurements of atomic lifetimes [5] or oscillator strengths [6]. Hence, experimentally determined polarizabilities are useful for testing atomic theory.

Cesium is used in a number of important applications including atomic clocks [7], laser cooling [8], and parity violation experiments [9]. It is an alkali atom and is therefore relatively easily modeled since it has only a single valence electron. Furthermore, it has transitions accessible to lasers and a relatively low melting point which facilitates the production of an atomic beam. The polarizabilities of the $6P_{1/2,3/2}$ states [10,11] and of the $(10-13)S_{1/2}$ states [12] have been measured with accuracies exceeding 0.1%. Recently, we determined the scalar and tensor polarizabilities of the $11D_{3/2,5/2}$ states and showed that the Stark mixing of these two fine structure states needed to be taken into account. [13] The purpose of this work is to report the polarizabilities for six additional D states having significantly different fine structure splittings.

The cesium D states are described by the Hamiltonian [14]

$$H=a\vec{L}\cdot\vec{S}-\left\{\alpha_0+\alpha_2\frac{3L_z-\vec{L}^2}{L(2L-1)}\right\}\frac{E^2}{2}, \tag{1}$$

where the first term is the spin-orbit interaction, a is the coupling constant, $\vec{L}$ is the orbital electronic angular momentum, and $\vec{S}$ is the electronic spin. The second term describes the Stark shift due to an external electric field $\vec{E}$. α_0 and α_2 are the scalar and tensor polarizabilities, respectively. The term containing α_2 vanishes when $L<1$. For low electric fields the eigenstates are approximately given by $|Jm_J\rangle$, where m_J is the azimuthal quantum number corresponding to the total electronic angular momentum J. The eigenenergies are then given by

$$\mathcal{E}=\frac{K}{2}E^2, \tag{2}$$

where K is called the Stark shift rate and is given by [13,14]

$$K(D_{5/2},|m_J|=\tfrac{1}{2})=-\alpha_0(D_{5/2})+\frac{4}{5}\alpha_2(D_{5/2})+\frac{3}{250}\frac{\alpha_2(D_{5/2})^2}{a}E^2,$$

$$K(D_{5/2},|m_J|=\tfrac{3}{2})=-\alpha_0(D_{5/2})+\frac{1}{5}\alpha_2(D_{5/2})+\frac{9}{125}\frac{\alpha_2(D_{5/2})^2}{a}E^2,$$

$$K(D_{5/2},|m_J|=\tfrac{5}{2})=-\alpha_0(D_{5/2})-\alpha_2(D_{5/2}),$$

$$K(D_{3/2},|m_J|=\tfrac{1}{2})=-\alpha_0(D_{3/2})+\alpha_2(D_{3/2})-\frac{6}{245}\frac{\alpha_2(D_{3/2})^2}{a}E^2,$$

$$K(D_{3/2},|m_J|=\tfrac{3}{2})=-\alpha_0(D_{3/2})-\alpha_2(D_{3/2})-\frac{36}{245}\frac{\alpha_2(D_{3/2})^2}{a}E^2. \tag{3}$$

The apparatus has been previously discussed and is therefore only briefly described [10]. A diode laser excited cesium atoms in an atomic beam to the $6P_{3/2}$ state. One of the $(10-13)D_{3/2,5/2}$ states was then populated using light generated by a ring dye laser (Coherent 699). The atoms were excited by the laser beams as they traversed a field-free region and subsequently when they passed through a uniform electric field which was generated by applying a voltage across two parallel stainless steel plates. Fluorescence, produced by the radiative decay of the atoms, was detected by two photomultipliers. The two fluorescence signals were processed by separate lock-in amplifiers whose reference was provided by a chopper that modulated the dye laser beam.

The procedure was to first determine the Stark shift rates K of the $|D_{3/2},|m_J|=\frac{1}{2}\rangle$ and $|D_{5/2},|m_J|=\frac{1}{2},\frac{3}{2}\rangle$ states. This

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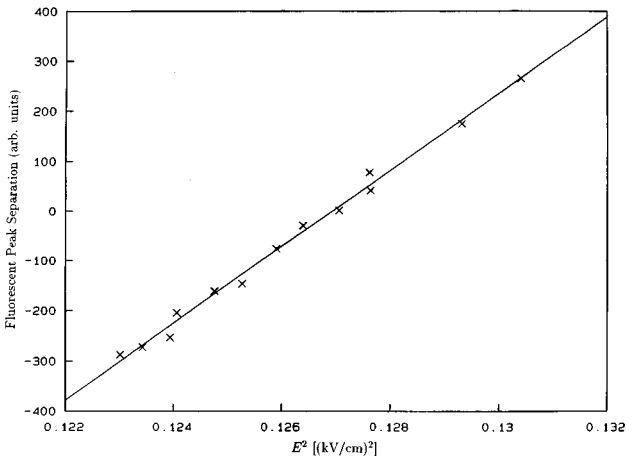

FIG. 1. Fluorescent peak separation vs electric field squared for the $13D_{5/2}|m_J|=\frac{1}{2}$ levels. The frequency difference measured in arbitrary units between the peak produced by the laser excitation of the atoms in the electric field and the peak generated by the laser beam shifted by 2000.000 MHz in the field-free region is plotted.

was done by measuring the electric field required for atoms excited by the dye laser beam to be simultaneously in resonance as atoms excited in a field free region by dye laser light which was frequency shifted 2000.000 MHz by an electro-optic modulator (New Focus 4421). The Stark shift was then plotted versus the square of the electric field. Figure 1 displays sample data taken for the $|13D_{5/2},|m_J|=\frac{1}{2}\rangle$ state. A line was fit to the data to find the electric field giving zero fluorescent peak separation. The Stark shift rate K was then found using Eq. (3) where the small dependence on E^2 was also taken into account. This procedure was repeated for the $|13D_{5/2},|m_J|=\frac{3}{2}\rangle$ and $|13D_{3/2},|m_J|=\frac{1}{2}\rangle$ states. The Stark shift of the $|m_J|=\frac{3}{2}$ levels of the $(10-13)D_{3/2}$ states has a strong nonquadratic dependence on the electric-field strength due to Stark mixing of the fine structure states. This is illustrated in Fig. 2 for the $13D_{3/2}$ state. These data were therefore analyzed by fitting a curve of the form $y=AE^2+BE^4+CE^6$ where Eq. (3) shows $A=-[\alpha_0(D_{3/2})+\alpha_2(D_{3/2})]/2$.

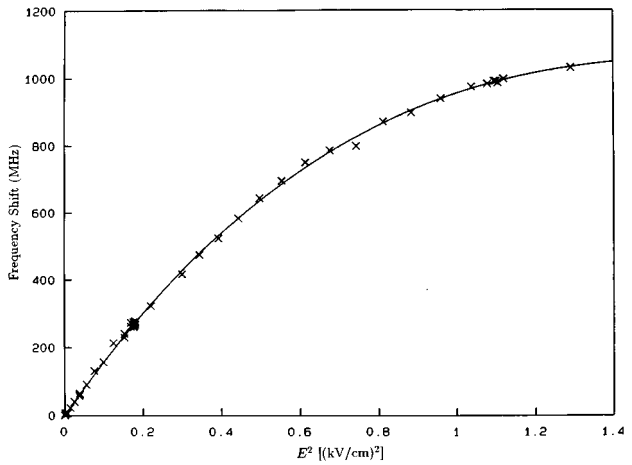

FIG. 2. Frequency shift vs electric field squared for the $13D_{3/2}|m_J|=\frac{3}{2}$ levels. The fitted curve is given by $y=1664E^2-848E^4+138.5E^6$, where y is the frequency shift (MHz) and E is the electric field measured in kV/cm.

TABLE I. Scalar and tensor polarizabilities. Units are MHz/(kV/cm)^2.

State	α_0	α_2	Reference
$10D_{3/2}$	-1041.3 ± 0.9	846.3 ± 0.9	This work
	-1050	848	Theory [16]
	-1150 ± 170	840 ± 40	[15]
$10D_{5/2}$	-1319.5 ± 2.1	1695.7 ± 4.9	This work
	-1319	1704	Theory [16]
	-1340 ± 130	1770 ± 90	[15]
$11D_{3/2}$	-2694.6 ± 2.7	2107.5 ± 2.7	[10]
	-2712	2120	Theory [16]
$11D_{5/2}$	-3379.5 ± 5.4	4242.1 ± 11.4	[10]
	-3384	4255	Theory [16]
	-3790 ± 350	4010 ± 400	[15]
$12D_{3/2}$	-6180 ± 4.9	4691.4 ± 4.9	This work
	-6245	4753	Theory [16]
$12D_{5/2}$	-7660 ± 15	9501 ± 39	This work
	-7738	9530	Theory [16]
$13D_{3/2}$	-12935 ± 18	9620 ± 18	This work
	-12989	9679	Theory [16]
$13D_{5/2}$	-16001 ± 25	19406 ± 49	This work
	-16099	19533	Theory [16]
		19000 ± 1000	[15]

The results for the polarizabilities are listed in Table I. The tensor polarizabilities are more accurate than those existing in the literature for any atomic state. The uncertainties are due primarily to the determination of the electric field arising from the measurement of the plate spacing and voltage. The results have been compared to the experiment by Fredriksson and Svanberg [15], who used a lamp to excite the $6P_{3/2}$ state and therefore had a lower signal-to-noise ratio. Their experiment also had a lower accuracy than the present work because of greater uncertainties in the determination of the electric field and the measurement of frequency shifts.

Table I also compares the results to those computed using a so-called Coulomb approximation which models the interaction of the outer valence electron with the nucleus and inner electron core by a Coulomb potential. This approximation has been shown to work well for excited $S_{1/2}$ states in cesium [16] but does not take into account the fine structure splitting which varies from 51 GHz for the $13D_{3/2,5/2}$ states to 140 GHz for the $10D_{3/2,5/2}$ states. However, Table I shows that the computed polarizabilities are all within 1% of the measured results. It is interesting to note that with the exception of the $10D_{5/2}$ state, the magnitude of the experimentally determined data is slightly smaller than the computed values. This can be taken into account when estimating the polarizabilities of states for which measurements have not been made. In conclusion, the Coulomb approximation can be used to estimate scalar and tensor polarizabilities to better than 1% for D states having a fine structure splitting of less than several hundred GHz.

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