Hyperfine-structure measurement of the 7S state of cesium

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The hyperfine structure of the $7S_{1/2}$ state of ^{133}Cs has been measured with the use of laser spectroscopy on a cesium atomic beam. We find the magnetic dipole coupling constant $A = 545.90(09)$ MHz. From the amplitude of the hyperfine components we find the ratio of the scalar to tensor polarizabilities ($|\alpha/\beta|$) for the $6S \rightarrow 7S$ transition to be 9.80(12).

The measurement of hyperfine structure has long been an important probe of atomic structure. For this reason, the hyperfine structure of the ground and excited states of alkali atoms has been studied extensively.[1] Information on the $7S_{1/2}$ state of cesium is particularly important at the present time because of its role in the study of parity violation in atoms.[2] In this paper we present a measurement of the hyperfine structure of the $7S_{1/2}$ state of ^{133}Cs obtained by studying the laser excited $6S_{1/2} \rightarrow 7S_{1/2}$ transition in the presence of an electric field. By measuring the separation of the hyperfine components we determine the hyperfine splitting of the $7S_{1/2}$ state to considerably higher precision than all other measurements of alkali excited-state hyperfine splittings. In addition, by comparing the amplitudes of the components we obtain the ratio between the scalar and tensor polarizabilities of the $6S_{1/2}$-$7S_{1/2}$ Stark dipole matrix element. A measurement of this ratio is of interest because the previous two measurements of this quantity are in serious disagreement.[3,4]

The $S_{1/2}$ levels of cesium are split into hyperfine doublets with total angular momentum $F=3$ and 4. Thus, in a dc electric field $\vec{E}$, a linearly polarized laser will excite four transitions having the intensities and frequency separations shown below:

$$\left.\begin{aligned} &6S_{F=3} \rightarrow 7S_{F=4},\ I_{43} = 21\beta^2 E_\perp^2, \\ &\qquad\qquad\qquad\qquad \Big\}\Delta\nu_1 = \Delta_{7S\,\mathrm{hf}}, \\ &6S_{F=3} \rightarrow 7S_{F=3},\ I_{33} = 7\beta^2 E_\perp^2 + 28\alpha^2 E_\parallel^2, \\ &\qquad\qquad\qquad\qquad \Big\}\Delta\nu_2 = \Delta_{6S\,\mathrm{hf}} - \Delta_{7S\,\mathrm{hf}} \\ &6S_{F=4} \rightarrow 7S_{F=4},\ I_{44} = 15\beta^2 E_\perp^2 + 36\alpha^2 E_\parallel^2, \\ &\qquad\qquad\qquad\qquad \Big\}\Delta\nu_3 = \Delta_{7S\,\mathrm{hf}} \\ &6S_{F=4} \rightarrow 7S_{F=3},\ I_{34} = 21\beta^2 E_\perp^2. \end{aligned}\right. \tag{1}$$

The subscripts $\perp$ and $\parallel$ are with respect to the direction of laser polarization, α and β are the scalar and tensor polarizabilities,[3] respectively, and $\Delta_{6S\,\mathrm{hf}}$ and $\Delta_{7S\,\mathrm{hf}}$ are the hyperfine splittings of the $6S$ and $7S$ states. In addition to the electric dipole intensities shown, each transition has a magnetic dipole amplitude. For the electric fields we used ($\sim$5000 V/cm), these contribute less than 1 part in 10^4 and can be neglected.

Since $\Delta_{6S\,\mathrm{hf}}$ is the primary standard of frequency, measuring the ratio of either $\Delta\nu_1$ or $\Delta\nu_3$ to $\Delta\nu_2 + \Delta\nu_3$ yields $\Delta_{7S\,\mathrm{hf}}$. Although the individual transition energies are electric field dependent, the separations, to a very good approximation, are not.[5] The ratio α/β is obtained from the ratios I_{44}/I_{34} and I_{33}/I_{43}.

The apparatus used is shown schematically in Fig. 1. A collimated beam of atomic cesium is produced in a manner similar to that given in Ref. 6. A secondary collimator further reduces the divergence to about 0.025 rad. This beam intersects a standing wave laser field at right angles in a region of static electric field. The static field is obtained by applying 5000 V to optically transparent-electrically conducting coated glass plates (not shown in figure) which sit 0.5 cm above and below the laser beam. The standing wave field is provided by a spherical mirror Fabry-Perot interferometer (power enhancement interferometer). The output from a single frequency ring dye laser (Spectra Physics model No. 380) with homemade frequency stabilization[7] is circularly polarized and modematched into the interferometer. One of the interferometer mirrors is mounted on a piezoelectric transducer, thereby allowing the interferometer resonance to be electronically locked to the laser frequency. The dye laser output is typically 0.1 to 0.2 W at 540 nm and the interferometer increases the electromagnetic field strength by a factor of 12.5. The short term laser frequency jitter is about 0.5 MHz peak to peak.

Five percent of the dye laser beam is sent into an

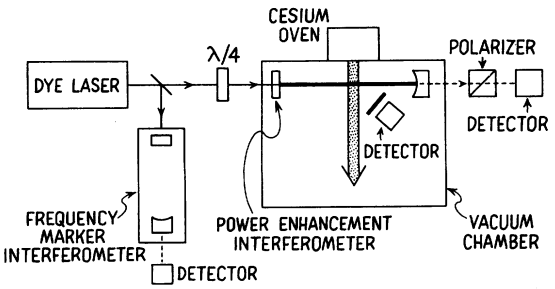

FIG. 1. Schematic of apparatus.

additional fixed length Fabry-Perot interferometer which is thermally insulated and hermetically sealed (frequency marker interferometer). The resonances of this cavity provide a frequency scale.

The $6S \rightarrow 7S$ transition is detected by a silicon photodiode which sits under the lower electric field plate. This diode monitors the 850- and 890-nm light which is emitted in the $6P_{1/2,3/2} \rightarrow 6S$ step of the cascade decay of the $7S$ state. A colored glass cutoff filter prevents the scattered 540-nm light from reaching the detector. The photodiode output goes into a preamp followed by a precision voltage divider. The linearity of the photodiode preamp combination is better than 1 part in 10^4. The voltage divider is used to reduce the $3 \rightarrow 3$ and $4 \rightarrow 4$ transitions signals by a factor of 155.44, making them approximately the same size as the undivided $4 \rightarrow 3$ and $3 \rightarrow 4$ transitions.

Other photodiodes measure the light transmitted through the frequency marker and power enhancement interferometers. These three signals and the voltage ramp which scans the laser frequency are digitized and stored by a PDP-11 computer for off-line analysis.

Spectra were obtained by scanning the laser frequency over each of the hyperfine transitions. For each transition the scan lasted about 1 min and covered about 1 GHz. For each of the three separations a set of about 15 scans were made by alternating between the two transitions of interest. Typical scans are shown in Fig. 2. The 20-MHz linewidth is primarily due to the cesium beam divergence. The marker interferometer is intentionally adjusted to obtain the rather complex signal shown. This structure corresponds to exciting a number of nondegenerate modes and is useful for checking for and correcting scan nonlinearities.

Analysis and results. To find the hyperfine splitting $\Delta_{7S\,\mathrm{hf}}$, the spectra were first normalized to the instantaneous laser intensity. The line centers were then found in terms of the frequency marker scale. This was complicated by the thermal drift of the marker interferometer. To correct for the drift, the position of each transition relative to the frequency marker was found as a function of time. Because the thermal time constant of the interferometer was long, the drift was quite linear with time during each set and varied between 0 and 0.3 MHz per minute for the different sets. Having thus determined the drift, the results were corrected appropriately. Once the line separations were measured in terms of the frequency

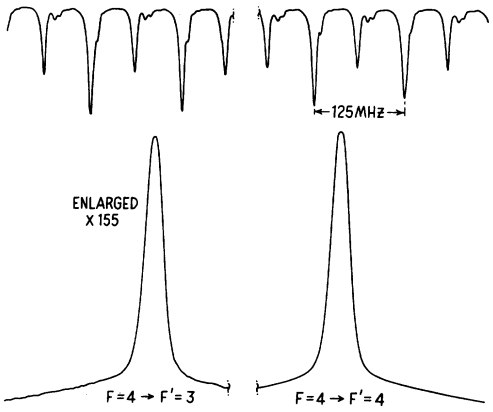

FIG. 2. Typical spectra.

marker, the separation between the $F=4 \rightarrow 4$ and $F=3 \rightarrow 4$ lines was used to determine the exact marker spacing. It is amusing to note that the interferometer length is thus known in terms of the fundamental frequency standard. Using this scale, $\Delta\nu_1$ and $\Delta\nu_3$ were found to be in excellent agreement and their combined average was 2,183.59(36) MHz $= 7S_{1/2}$ hyperfine splitting. This gives the magnetic dipole coupling constant $A = 545.90(09)$ MHz, which is in good agreement with the previous result of 546.3(30) MHz.[8] The uncertainty is primarily due to uncertainties in scan linearity and the correction for the drift of the frequency marker.

To find $|\alpha/\beta|$, the area under the four peaks were measured and the ratios I_{33}/I_{43} and I_{44}/I_{34} determined. The ratio $|\alpha/\beta|$ was then found using Eq. (1). The light transmitted through the enhancement interferometer was found to be imperfectly circularly polarized, resulting in a correction of 0.6%. From I_{33}/I_{43} we obtained $|\alpha/\beta| = 9.91(08)$, and from I_{44}/I_{34}, $|\alpha/\beta| = 9.68(08)$. Because these results did not seem consistent with a simple statistical variation we took the combined value to be 9.80(12), where the uncertainty covers both values. This is in good agreement with the value 9.91(11) of Ref. 4, but disagrees with the value 8.8(4) given in Ref. 3.

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[1]E. Arimondo, M. Inguscio, and P. Violino, Rev. Mod. Phys. 49, 31 (1977).
[2]M. A. Bouchiat and C. Bouchiat, J. Phys. (Paris) 35, 899 (1974).
[3]M. A. Bouchiat and L. Pottier, J. Phys. (Paris) Lett. 36, L189 (1975).
[4]J. Hoffnagle *et al.*, Phys. Lett. 85A, 143 (1981).
[5]M. Mizushima, *Quantum Mechanics of Atomic Spectra and Atomic Structure* (Benjamin, New York, 1970), Sec. 10-4.
[6]P. F. Wainwright, M. J. Algaurd, G. Baum, and M. S. Lubell, Rev. Sci. Instrum. 49, 571 (1978).
[7]C. E. Wieman and S. L. Gilbert, Opt. Lett. 7, 480 (1982).
[8]R. Gupta, W. Happer, L. K. Lam, and S. Svanberg, Phys. Rev. A 8, 2792 (1973).