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Precision measurement of the hyperfine structure of $8d\ ^2D_{3/2}$ state of ^{133}Cs by the radio-frequency phase modulation technique

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ABSTRACT

We report the measurement of the hyperfine structure in the $8d\ ^2D_{3/2}$ state of ^{133}Cs isotope by Doppler free two-photon fluorescence spectroscopy in a gas cell. The hyperfine level separations were measured by the radio-frequency phase modulation technique using a frequency stabilized Ti:sapphire laser. The frequency separation between various hyperfine levels of the excited state has been measured with a precision of ~60 kHz. From the measured hyperfine separations of the excited state, we have determined the magnetic dipole coupling constant (A) and the electric quadrupole coupling constant (B) for the $8d\ ^2D_{3/2}$ state. The determined hyperfine structure constants are $A=3.98$ (0.01) MHz and $B=-0.03$ (0.09) MHz. Our deduced magnetic dipole coupling constant (A) value is thus by far the most precise and was found to be in good agreement with the 3σ level with the earlier reported values. This work reports the electric quadrupole coupling constant (B) value for the $8d\ ^2D_{3/2}$ state for the first time.

1. Introduction

The hyperfine structures of alkali-metal atoms have been a subject of considerable attention, since the seventies as indicated from the comprehensive review by Arimondo et al. [1]. More recently, there has been renewed interest in the hyperfine structure of transitions of alkali-metals and in particular Cesium [2–7]. Gerginov and Tanner report a diode laser based system for precision frequency measurements of the ^{133}Cs $6p\ ^2P_{3/2}$ state hyperfine splittings [8]. On the other hand, d-state hyperfine structures remain a significant computational challenge because of strong correlation effects [9]. Extensive work on the precision measurements of the excited states of ^{133}Cs has been reported by both Doppler-free two-photon and step-wise excitation spectroscopy [3,10–21]. In the recent past, two-photon transitions of Cesium have become the subject of investigation in order to find new optical frequency references in the visible range [10]. Lorenzen and Niemax have made accurate measurements of the $n\ ^2S_{1/2}$ (n=9–30), $n\ ^2P_{1/2,\ 3/2}$ (n=9–50) and $n\ ^2D_{3/2,\ 5/2}$ (n=5, 8–32) energy levels in Cs I in the wavelength range 6379–7432 Å using either Doppler free two-photon spectroscopy or Doppler limited one photon spectroscopy with a frequency doubling crystal [11]. Van Wijngaarden and Sagle populated the $8d\ ^2D_{3/2}$ state by multi-photon excitation of the ground state and have measured the magnetic dipole coupling constant of this state to be 3.92 (0.10) MHz by using a magnetic field based decoupling of the nuclear and electronic angular momenta [12]. After this work, they [13] have reported the hyperfine structure of the $8d\ ^2D_{3/2}$, $9d\ ^2D_{3/2}$ and $10d\ ^2D_{3/2}$ excited states using quantum beat spectroscopy with improved precision. Confining and cooling of atomic Cesium in a magneto-optical trap and subsequent determination of the hyperfine structure constants of the $6d\ ^2D_{5/2}$ state by two-photon spectroscopy have been reported by Georgiades et al. [3]. Yei et al. have reported the precision measurement of the $5d\ ^2D_J$ (J=3/2 and 5/2) hyperfine structure in atomic Cesium using the pump–delayed probe method based on quantum beat spectroscopy [5]. Hagel et al. have performed accurate optical frequency measurement on the hyperfine components of the $6S$–$8S$ two-photon transition in Cesium with an uncertainty of 3×10^{-10} [10]. Sasaki et al. have reported the use of an extended cavity diode laser for studying the $6s\ ^2S_{1/2}\rightarrow8s\ ^2S_{1/2}$ two-photon transition in Cesium [14]. Kortyna et al. have investigated the hyperfine splittings and the hyperfine coupling constants for the $6d\ ^2D_{3/2}$ and $6d\ ^2D_{5/2}$ states of atomic Cesium, and have significantly improved the precision for the hyperfine coupling constants of the latter state using two-color absorption spectroscopy with sub-Doppler resolution [15]. Auzinsh et al. have studied both theoretically and experimentally the pure electric field level-crossing of m_F Zeeman sublevels of hyperfine F levels for the two-step laser excitation for the $n\ ^2D_{3/2}$ states in Cs for n=7, 9 and 10 [16]. Cheng et al. have studied the Cesium $6s\ ^2S_{1/2}\rightarrow8s\ ^2S_{1/2}$ two-photon-transition (TPT) and demonstrated that the Cesium TPT-stabilized diode laser

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could be a reliable frequency reference at 822.5 nm wavelength and the possible systematic errors were evaluated to be smaller than 2 kHz [17]. Kortyna et al. have also determined the hyperfine coupling constants of the $7d\ ^2D_{3/2}$ state using a radio-frequency phase modulation technique [18]. Stalnaker et al. [19] reported measurements of absolute transition frequencies and hyperfine coupling constants for the $8s\ ^2S_{1/2}$, $9s\ ^2S_{1/2}$, $7d\ ^2D_{3/2}$, and $7d\ ^2D_{5/2}$ states in ^{133}Cs vapor using femto-second frequency comb measurements. In a more recent work, Kortyna et al. have reported the scalar and tensor polarizabilities of the $6d\ ^2D_{3/2}$ state and have additionally determined the hyperfine coupling constants [20]. The hyperfine splitting of the $9s\ ^2S_{1/2}$ state for the ^{133}Cs isotope has been measured using Doppler-free two-photon fluorescence spectroscopy in a gas cell and the magnetic dipole constant for $9s\ ^2S_{1/2}$ has been reported by Kiran Kumar and Suryanarayana [21]. Very recently, we have also reported the measurement of hyperfine structure in the $7d\ ^2D_{3/2}$ state of ^{133}Cs isotope by Doppler-free two-photon fluorescence spectroscopy in a gas cell [22]. Generally, measurements of isotope shifts and hyperfine structure of odd isotopes is carried out [23–25] using a stabilized Fabry–Perot interferometer as a marker cavity for calibrating the laser frequency scan. With the advent of acousto-optic modulators, it was possible to frequency shift a laser by a specified amount. The frequency-shifted and unshifted laser beams were then superimposed to excite an atomic beam. With a precisely known shift in the frequency, accurate determination of transition isotope shifts and hyperfine splitting has been reported [26,27]. It is apparent that the apparatus is much simpler than interferometers, however, the drawback of the technique is the spatial shift associated with the frequency shifted beam. Hence, the exact overlaping of the frequency shifted and unshifted beams is very important, since a differential alignment produces a residual differential first-order Doppler shift. For more precise measurements, a transfer cavity was also utilized for many applications in which the cavity length of the transfer cavity must be stabilized with a reference laser. This reference laser in turn is locked to an atomic transition for an accurate calibration [28-30]. Unfortunately, the equipment required is relatively complex and expensive.

The hyperfine structure of the $8d\ ^2D_{3/2}$ state in ^{133}Cs has been previously investigated by Svanberg et al. [31], Hogervost and Svanberg [32], Svanberg and Tsekeris [33], Deech et al. [34,35] Lorenzen and Niemax [11] and van Wijngaarden and Sagle [12,13]. In the present work, we have measured the hyperfine structure constants for this state with a precision of few tens of kHz. The method used for the present work was based on the radio-frequency (rf) phase modulation technique [15,18,20,36–38]. Such a method was recently reported by Mingwu Lu et al. [39] for the measurement of hyperfine separations of the 741 nm transition in Dy. Since, the method [22] of using a frequency-stabilized Ti: sapphire laser locked to one of the hyperfine transitions and an acousto-optic modulator locked to another hyperfine transition requires very high powers at the excitation wavelength for carrying out Doppler-free two-photon spectroscopy in two identical setups, we have adopted the radio frequency phase modulation technique for the measurement of hyperfine structure of the Cs $8d\ ^2D_{3/2}$ state. The technique of radio-frequency phase modulation of the laser by using a broadband electro-optic modulator for the generation of sidebands to the atomic spectra has also been applied by Deilamian et al. [40] and Leefer et al. [41]. We have earlier utilized [37] a similar technique for the measurement of the transition isotope shift, hyperfine splittings and the magnetic dipole constant (A) for the excited $6s\ ^2S_{1/2}$ state of both the isotopes of atomic potassium. This calibration technique provides adequate precision without the exact mechanical and thermal requirements associated with interferometric methods. In this paper, the hyperfine separations of the Cs $8d\ ^2D_{3/2}$ state have been measured with a precision of $\sim$60 kHz using Doppler-free two-photon spectroscopy. We have used a single-mode cw Ti: sapphire laser pumped by a 10 W diode pumped solid state (DPSS) laser to achieve sub-Doppler resolution in a two-photon fluorescence spectroscopy setup. We adopted the simpler method of using an electro-optic modulator for frequency measurements and the results are compared with previous measurements. From the measured hyperfine separations of the excited state, we have determined both the hyperfine coupling constants (A and B) for the excited $8d\ ^2D_{32}$ state with a high precision and have also compared our results with earlier measurements.

2. Experiment

The experimental layout for the measurement of hyperfine splitting by detecting the fluorescence has been depicted in Fig. 1. The two-photon transition in Cs atoms in a gas cell has been induced by a DPSS pumped cw ring Ti:sapphire laser. The linewidth of the Ti:sapphire laser is about 60 kHz when actively

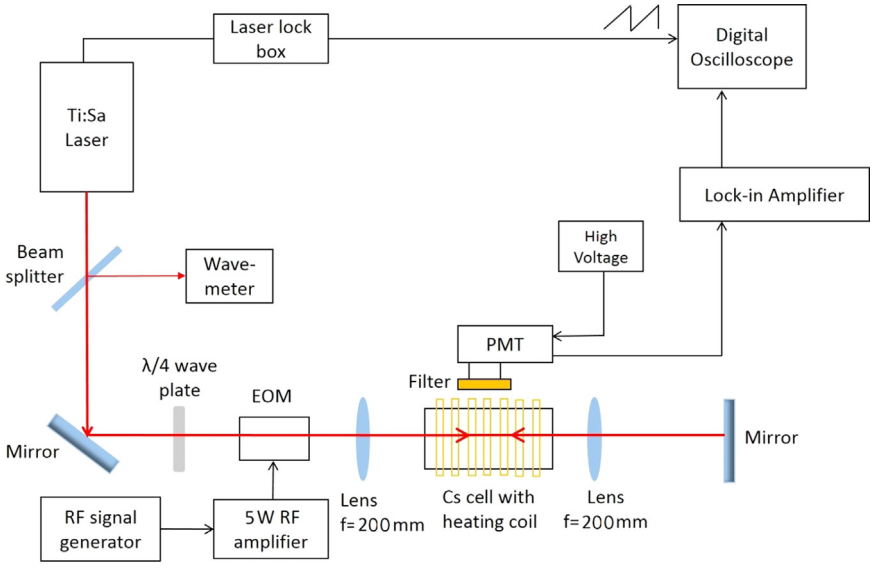

Fig. 1. Schematic of the experimental setup.